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METHOD OF GENERATING ENERGY EFFICIENT CODES

Abstract. The article considers the current problem of reducing the power that is dissipated in global communication lines while maintaining high performance. High switching activity leads to significant losses through coupling capacities between long lines. They are one of the most energy-intensive components of the embedded system. The use of Gray codes not only reduces dynamic energy losses in the address bus, but also minimizes communication losses between closely spaced lines. However, the Gray code has low balance and a large number of bit switches. The methods for constructing alternative Gray codes are investigated, which makes it possible to reduce the number of switches on the buses. The purpose of the article is to develop a method for constructing unit distance codes, determining the type of code transformations and forming a system of various typical representatives. Estimates of their number are obtained, characteristics are determined, catalogs of typical representatives are formed. The application of the developed method will make it possible to analyze and select codes with the best properties and, as a result, obtain the best results in terms of network delays, energy costs and other design constraints for computer systems.

Keywords: coding, unit distance codes, energy efficient coding, switching activity, equivalence.

Introduction

Statement of the problem. Computer systems are widely used in various fields of science and technology to build systems for controlling, regulating, transmitting, and processing discrete information.

Modern processors are becoming increasingly bottlenecked by the energy required to move data across different levels of the memory hierarchy and between different input and output devices.

High switching activity leads to significant losses due to capacitance between long lines. They are one of the most power-consuming components of an embedded system [1, 2].

Various methods are used to encode the address bus with the least switching activity. Gray codes are used to reduce dynamic energy. Since access to the instruction memory is often continuous, the use of Gray codes not only reduces dynamic energy losses in the address bus, but also minimizes communication losses between closely spaced lines. However, the Gray code has a low balance and a large number of bit changes [3, 4]. In this regard, the problem of finding low-power coding methods that allow efficient transmission or storage of information is relevant.

Analysis of recent studies and publications. Gray codes are widely used in practice, but they have low balance and, in some cases, cannot be used. In this regard, alternative coding options are being sought [5, 6].

The conceptual foundations of Gray transforms are considered in the works of A. Beletsky [7, 8]. A generalized structure of Gray codes is proposed, which includes the classical “left-handed” and the proposed “right-handed” Gray codes. In the new class of right-handed transformations, the value of the lowest (right) bit of the transformed number remains unchanged during forward and reverse transformations. The introduction of the left and right Gray transforms (both forward and backward) together with the reverse permutation of the codes led to the possibility of constructing combined or composite Gray codes. The use of composite Gray codes has proven to be quite successful in cryptography, in solving problems of synthesis and analysis of discrete systems. The author considered the properties of transformations for only three bits.

Paper [9] presents algorithms for generating reflected and modular (shifted) m-ary Gray codes. For both variants, the ranking and de-ranking functions are presented, as well as algorithms for generating codewords between two given vectors. A. Phillips and M. Wick [10] developed a recursive method for creating n-bit binary Gray codes. The paper [11] proposes innovative approaches to generating classical and quantum reflected binary Gray codes. A technique is described that generates both long and short Gray codes with the desired properties of the same number of column changes. M. Ali [12] developed a method for constructing an n-bit reflected binary Gray code sequence in space and time.

T. Mutze and J. Nummenpalo studied the Gray code at medium levels, which is a cyclic enumeration of all 2n+1 bit strings with n or n+1 entries equal to 1, such that any two consecutive bit strings in the list differ by exactly one bit for any integer n. They also provided an efficient algorithm for computing the Gray code at medium levels [13].

For image denoising, Y. Zhou, K. Panetta and C. Chen proposed a new parametric n-dimensional Gray code, the so-called (n, k, p)-Gray code, which includes well-known codes such as the binary-reflected code and the (n, k)-Gray code [14]. The (n, k, p)-Gray code varies depending on the values of the base n and the distance parameter p. It is a new type of non-Boolean Gray code when its base is greater than two. X. Wang, Y. Su and H. Zhang proposed to use the (n, k, p)-Gray code for encrypting color images [15]. Experimental results have shown that the encryption algorithm shows high performance in image encryption. It can be used to protect privacy in biometrics, medical imaging systems, and video surveillance systems. M. Tahiri, H. Karmouni, and A. Bencherqui used the (n, k, p)-Gray code to develop a hybrid optimization and fractional transform algorithm [16].

The article [17] considers the problem of constructing Gray codes using mathematical methods. The authors analyze methods for constructing Gray codes using Hamiltonian graphs and the iterative method. The problem of generating Gray codes of any given length is considered. G. Meenakshi and S. Gupta in [18] proposed an algorithm for generating (n, r) Gray codes. As an example, they consider the design details of the generalized binary Gray code for 5 and 6 bits.

An analysis of known studies has shown that there are other codes that have the same characteristics as Gray codes. This class of codes is called generalized (alternative, extended) Gray codes in the literature. The name "unit-distance codes" reflects the properties of these codes more accurately.Unfortunately, most of the researchers study only particular cases of codes, and there is no general approach to their study.

Aim of the article: development of a method for constructing unit distance codes and forming systems of typical representatives.

Presentation of the main study material

In general, a code is a bijective mapping of a finite ordered set of symbols belonging to some finite alphabet Y to another, not necessarily ordered set of symbols X to encode the transmission, storage, or transformation of information [20, 21]. For codes, the bijective function has the form f: Y → X, where X is a set of codewords, $X = \{X^1, X^2,\dots,X^k\}$; Y is a finite ordered set of symbols, $Y = \{y_1,y_2,\dots,y_k\}$, k is the number of codewords, n is the number of bits of a binary code.

The code word X^i consists of n characters (the number of bits):

$$X^i = \{x^i_1 \dots x^i_n\};\ x^i_j \in \{0,1\},\quad i=1,\dots,k;\quad j=1,\dots,n,$$

where k is the number of codewords, n is the number of bits of the binary code.

Two adjacent words differ only in one bit, i.e.

$$\rho(X^i, X^{i+1}) = 1,\quad i = 1,\dots,k-1, \tag{1}$$

where ρ is the Hamming distance between codewords X^i and X^{i+1}.

The code in which $\rho(X^1, X^k) = 1$ is called cyclic. The canonical form of a code W(X) is its representation in the form:

$$W(X) = x^1_1 \dots x^1_n \dots x^i_1 \dots x^i_n \dots x^k_1 \dots x^k_n. \tag{2}$$

For compactness, the binary form of the representation W(X) can be converted to hexadecimal.

On the set of unit distance codes, the following types of transformations are considered: column permutation (P transformation) and column inversion (N transformation). These transformations preserve the property of unit distance between adjacent binary words in the code. The set of transformations is denoted by $\Pi = \{\pi_1,\dots,\pi_{Lpn}\}$, where L_{PN} is the number of PN transformations.

The X^i code corresponds to the canonical form $W(X^i)$. As a result of the transformation π_j, code X^i is transformed into code X^i_j with the canonical form $W(X^i_j)$. A typical representative of a code X^i is a code (denoted by $T(X^i)$) that has the smallest canonical form in the lexicographic sense among the codes obtained as a result of a set of P transformations, i.e.

$$T(X^i) = \min\{W(X^i_j)\};\ j=1,\dots,L_{PN}. \tag{3}$$

Based on the set of typical representatives, a set of different typical representatives is formed $MT = \{T^1,\dots,T^{KT}\}$, where KT is the number of different typical representatives. For each typical representative included in this set, its structure is determined $S(X) = \langle H(X),\le\rangle$, where

$$h_i = \sum_{j=2}^{k} (x_{i,j-1} \oplus x_{i,j}),\ i = 1,\dots, n. \tag{4}$$

The balance of C code is defined as follows:

$$C = \sum_{i=1}^{n} \left| h_i \cdot \sum_{j=1}^{n} h_j \Big/ n \right|. \tag{5}$$

Typical representatives T^1 - T^{KT} are divided into non-intersecting equivalence classes S. Typical representatives T^i and T^j are called S-equivalent if $S(T^i) = S(T^j)$. As a result, a set of typical S-equivalent representatives is formed, denoted by $MS = \{S^1,\dots,S^{NS}\}$, where NS is the number of typical S-equivalent representatives.

To build a system of typical representatives for a group of Π transformations, a procedure has been developed, which is described using the following notation:

i - the current number of the code under review,

X^i - the code under consideration

$T(X^i)$ - a typical representative of the codeX^i,

S^i - the structure of code X^i,

KT - the number of different typical representatives,

MT - the set of different typical representatives,

KS - the number of code structures,

MS – the set of code structures,

$KTC(S_j)$ - the number of different typical representatives that have the structureS_j, j = 1,...,KS.

$MTC(S^j, KTC(S^j))$ - the set of different different typical representatives that have the structure S^j.

The procedure for constructing a system of typical representatives for a group of Π transformations consists of the following steps.

1. i = 0.
2. KT = 0, KS = 0.
3. i = i +1.
4. Let's form the step X^i.
5. We define a typical code representative X^i - $T(X^i)$.
6. We define the code X^i - S^i structure.
7. If $T(X^i) \in$ MT, then proceed to the stage 19.
8. KT = KT + 1.
9. $MT(KT) = T(X^i)$.
10. If $S^i \in$ MS, then proceed to the stage 12.
11. Proceed to the stage 15.
12. $KTC(S^i) = KTC(S^i) + 1$.

13. $MTC(S^i, KTC(S^i)) = T(X^i)$.
14. Proceed to the stage 19.
15. KS = KS +1.
16. $MS(KS) = S^i$.
17. $KTC(S^i) = 1$.
18. $MTC(S^i, KTC(S^i)) = T(X^i)$.
19. If all code options are considered, then proceed to the stage 21.
20. Proceed to the stage 3.
21. End.

Table 1 shows an example of building a system of typical representatives for a group of Π transformations.

Table 1 – **An example of building a system of typical representatives for a group of Π transformations**

i	X^i	$T(X^i)$	S^i	MT	MS
1	01326457fb98aecd	01326457fb98aecd	1356	MT(1) = T(X1)	MS(1) = S1
2	01326457fb9dc8ae	01326457fb9dc8ae	1455	MT(2) = T(X2)	MS(2) = S2
3	01326457fb9dcea8	01326457fb9dcea8	1446	MT(3) = T(X3)	MS(3) = S3
4	01326457fba89dce	01326457fba89dce	1356	MT(4) = T(X1)	
5	01326457fbaec89d	01326457fbaec89d	1455	MT(5) = T(X5)	
6	01326457fbaecd98	01326457fbaecd98	1446	MT(6) = T(X6)	
7	01326457fd98ceab	01326457fd98ceab	1455	MT(7) = T(X7)	
8	01326457fd9ba8ce	01326457fd9ba8ce	1347	MT(8) = T(X8)	MS(4) = S8
9	0132a89bfd5764ce	01326457fd9ba8ce	1347	T(X9)∈MT	
10	0132abfd98c4576e	013267fd54c89bae	3336	MT(9) = T(X10)	MS(5) = S10
11	0132abfd98ce6457	013267fd54cea89b	2355	MT(10) = T(X11)	MS(6) = S11
12	0137feab98cd5462	0137feab98cd5462	2346	MT(11) = T(X12)	MS(7) = S12
13	01546237fd9baec8	01326457fb9dcea8	1446	T(X13)∈MT	
14	015467fb32a89dce	013267fd54c89bae	3336	T(X14)∈MT	
15	0154cdfb98a2376e	013267fd54c89bae	3336	T(X15)∈MT	
16	0154cdfb98ae6237	013267fd54cea89b	2355	T(X16)∈MT	
17	015d9b32a8cef764	01375d98c46efba2	3444	MT(12) = T(X17)	MS(8) = S17
18	015d9b37fe62a8c4	01375d9bfea8c462	2256	MT(13) = T(X18)	MS(9) = S18
19	015dfb98aec46732	0137fd54ce62ab98	2445	MT(14) = T(X19)	MS(10) = S19
20	015dfb98c46732ae	0137fd5462ab98ce	3345	MT(15) = T(X20)	MS(11) = S20
21	015dfb98c46ea237	0137fd5462aec89b	3345	MT(16) = T(X21)	
22	015dfb98cea23764	0137fd546ec89ba2	2445	MT(17) = T(X22)	
23	015dfe64c89ba237	0137fea2645dc89b	3345	MT(18) = T(X23)	
24	015dfe6732ab98c4	0137feab98cd5462	2346	T(X24)∈MT	
25	015dfea23764c89b	0137fec89ba2645d	3345	MT(19) = T(X25)	
26	0198a2376ec45dfb	0132645dcea89bf7	2355	MT(20) = T(X26)	
27	0198a23bf7546ecd	01326457fd98ceab	1455	T(X27)∈MT	
28	0198a23bf75dc46e	01326457fd9ba8ce	1347	T(X28)∈MT	
29	0198a23bf75dce64	01326457fd9baec8	1446	MT(21) = T(X29)	
30	0198a23bf7645dce	01326457fdc89bae	1356	MT(22) = T(X30)	
31	0198a23bf76ec45d	01326457fdcea89b	1257	MT(23) = T(X31)	MS(12) = S31
32	0198c45df76ea23b	01326457fdcea89b	1257	T(X32)∈MT	
33	019d573bfea264c8	01375d9bfea8c462	2256	T(X33)∈MT	
34	023bae64c89df751	01375d98c46efba2	3444	T(X34)∈MT	
35	023bae64cdf75198	01375d98cefba264	2445	MT(24) = T(X35)	
36	023bae67fd5198c4	01375d9bfea264c8	2346	MT(25) = T(X36)	
37	023bae67fd54c891	01375d9bfea8c462	2256	T(X9)	
38	023bae67fd9154c8	01375d9bfe62a8c4	2445	MT(26) = T(X38)	
39	023bae67fd98c451	01375d9bfe64c8a2	2445	MT(27) = T(X39)	
40	023bae67fdc45198	01375d9bfec8a264	2256	MT(28) = T(X40)	
41	02a8c46efb319d57	01326457fb98aecd	1356	T(X41)∈MT	
42	045dce62a8913bf7	01375d98c462aefb	3336	MT(29) = T(X42)	
43	045dce62a89bf731	01375d98c46efba2	3444	T(X43)∈MT	
44	0462a8cef7315d9b	01326457fba89dce	1356	T(X44)∈MT	
45	08a264cefb9d5137	01326457fb9dc8ae	1455	T(X45)∈MT	

Table 2 shows the formed system of different typical representatives. Table 3 shows the binary codes and their characteristics: binary positional code X^1, Gray code X^2, binary code X^3 (i = 17 in Table 1), corresponding to the structure $S(X^3) = \{3,4,4,4\}$and its typical representative X^4. Fig. 1 shows the assessment of the options' balance. The number of changes in the values of each bit for these codes is as follows: $H^1=\{1,3,7,15\}$, $H^2 = \{1,2,4,8\}$, $H^3 = \{4,3,4,4\}$, $H^4 = \{4,4,3,4\}$. The values of the balance of the codes: $C^1 = 4,5$; $C^2 = 9$; $C^3 = 1,5$; $C^4 = 1,5$. A comparative analysis of the results shows that the type of code significantly affects its characteristics.

Thus, in the above example, the balance of the obtained typical representative ^{X4} is 6 times better than this indicator in the Gray code.

Table 2 – **System of different typical representatives**

KS	S	KTC (KS)	MTC(S)	KS	S	KTC (KS)	MTC(S)
1	1257	1	01326457fdcea89b	8	2355	1	013267fd54cea89b
2	1347	1	01326457fd9ba8ce			2	0132645dcea89bf7
3	1356	1	01326457fb98aecd	9	2445	1	0137fd54ce62ab98
		2	01326457fba89dce			2	0137fd546ec89ba2
		3	01326457fdc89bae			3	01375d98cefba264
4	1446	1	01326457fb9dcea8			4	01375d9bfe62a8c4
		2	01326457fbaecd98			5	01375d9bfe64c8a2
		3	01326457fd9baec8	10	3336	1	013267fd54c89bae
5	1455	1	01326457fb9dc8ae			2	01375d98c462aefb
		2	01326457fbaec89d	11	3345	1	0137fd5462ab98ce
		3	01326457fd98ceab			2	0137fd5462aec89b
6	2256	1	01375d9bfea8c462			3	0137fea2645dc89b
		2	01375d9bfec8a264			4	0137fec89ba2645d
7	2346	1	0137feab98cd5462	12	3444	1	01375d98c46efba2
		2	01375d9bfea264c8				

Table 3 – **Binary codes and their features**

X^1				X^2				X^3				X^4			
x^1_1	x^1_2	x^1_3	x^1_4	x^2_1	x^2_2	x^2_3	x^2_4	x^3_1	x^3_2	x^3_3	x^3_4	x^4_1	x^4_2	x^4_3	x^4_4
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1
0	0	1	0	0	0	1	1	0	1	0	1	0	0	1	1
0	0	1	1	0	0	1	0	1	1	0	1	0	1	1	1
0	1	0	0	0	1	1	0	1	0	0	1	0	1	0	1
0	1	0	1	0	1	1	1	1	0	1	1	1	1	0	1
0	1	1	0	0	1	0	1	0	0	1	1	1	0	0	1
0	1	1	1	0	1	0	0	0	0	1	0	1	0	0	0
1	0	0	0	1	1	0	0	1	0	1	0	1	1	0	0
1	0	0	1	1	1	0	1	1	0	0	0	0	1	0	0
1	0	1	0	1	1	1	1	1	1	0	0	0	1	1	0
1	0	1	1	1	1	1	0	1	1	1	0	1	1	1	0
1	1	0	0	1	0	1	0	1	1	1	1	1	1	1	1
1	1	0	1	1	0	1	1	0	1	1	1	1	0	1	1
1	1	1	0	1	0	0	1	0	1	1	0	1	0	1	0
1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	0

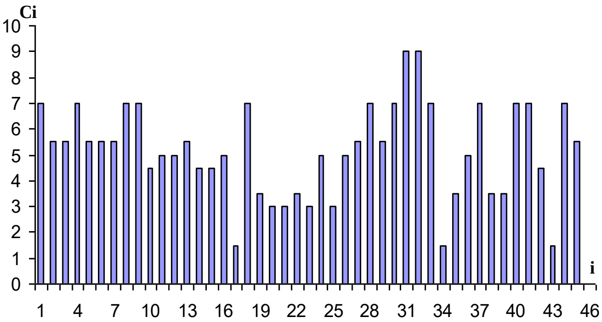

Fig. 1. Assessment of the options' balance

Conclusions from this study and prospects for further research in this area

The paper considers the actual problem of reducing power dissipation in global interconnection lines while maintaining high performance. It is shown that the switching activity of buses is the cause of a significant share of the total power dissipation. One of the effective methods for reducing switching activity during device-to-device or system-on-chip communication is the use of low-power coding methods.

A method for generating energy-efficient codes and systems of typical representatives is proposed, which allows choosing the optimal coding without going through the options. Estimates of the number of typical structures are obtained and catalogs of typical representatives are formed.

The application of the developed method will allow analyzing and selecting codes with better properties and obtaining better results in terms of network delays, energy costs, and other design constraints for computer systems.

Further research in this area: development of a method for constructing codes with specified properties and a method for constructing code converters.

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Метод формування енергоефективних кодів

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Анотація. У статті розглядається актуальна проблема зниження потужності, що розсіюється, в глобальних лініях зв'язку при збереженні високої продуктивності. Висока комутаційна активність призводить до значних втрат через ємності зв'язку між довгими лініями. Вони є одним із самих енергоємних компонентів убудованої системи. Використання кодів Грея не тільки зменшує динамічні втрати енергії в адресній шині, але також мінімізує втрати зв'язку між близько розташованими лініями. Однак, код Грея має низьку збалансованість і велику кількість перемикань бітів. Досліджено методи побудови альтернативних кодів Грея, що дозволяють зменшити кількість перемикань на шинах. Мета статті полягає у розробці методу побудови кодів одиничної відстані, визначення видів кодових перетворень та формування системи різних типових представників. Отримано оцінки їх кількості, визначено характеристики, сформовано каталоги типових представників. Застосування розробленого методу дозволить аналізувати та вибирати коди з найкращими властивостями та в результаті отримувати найкращі результати з погляду мережевих затримок, витрат на електроенергію та інших конструктивних обмежень для комп'ютерних систем.

Ключові слова: кодування, коди одиничних відстаней, енергоефективне кодування, комутаційна активність, еквівалентність.