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Optimal Golomb ruler sequence generation for FWM crosstalk elimination: Soft computing versus conventional approaches

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ABSTRACT

Four-wave mixing (FWM) crosstalk is the dominant nonlinear effect in long haul, repeaterless, wavelength division multiplexing (WDM) lightwave fiber optical communication systems. To reduce FWM crosstalk in optical communication systems, unequally spaced channel allocation method is used. One of the unequal bandwidth channel allocation techniques is designed by using the concept of Golomb ruler. It allows the gradual computation of an optimally allocated channel set such that degradations caused by inter-channel interference (ICI) and FWM is minimal. This paper applies two soft computing based approaches, i.e., Genetic Algorithm (GA) and Biogeography Based Optimization (BBO) to generate near-optimal Golomb ruler sequences in reasonable time. The generated sequences have been compared with the two other classical approaches namely Extended Quadratic Congruence (EQC) and Search Algorithm (SA). It has been observed that BBO/GA outperforms the other two approaches.

1. Introduction

In conventional wavelength division multiplexing systems, channels are usually assigned with center frequencies (or wavelength) equally spaced from each other. Due to equal spacing among the channels there is very high probability that noise signals (such as FWM signals) may fall into the WDM channels, resulting in severe crosstalk [1].

FWM crosstalk is the main source of performance degradation in all WDM systems. Performance can be substantially improved if FWM generation at the channel frequencies is avoided. It is therefore important to develop algorithms to allocate the channel frequencies in order to minimize the FWM crosstalk effect. The efficiency of FWM signals depends on the channel spacing and fiber dispersion [2,3]. If the frequency separation of any two channels of a WDM system is different from that of any other pair of channels, no FWM signals will be generated at any of the channel frequencies. This suppresses FWM crosstalk [4–7]. Thus, the use of proper unequal channel spacing keeps FWM signals from coherently interfering with the desired signals.

In order to reduce the FWM crosstalk effects in WDM systems, several unequally spaced channel allocation (USCA) techniques have been studied in literature [1,8–14]. An optimum-USCA (O-USCA) technique ensures that no FWM crosstalk signals will ever be generated at any of the channel frequencies if the frequency separation of any two channels is different from any other pair of channels in a minimum operating bandwidth [11].

Forghieri et al. [6] treated the *channel-allocation* design as an integer linear programming (ILP) problem by dividing the total available bandwidth into equal frequency slots. But the ILP problem was NP-complete and no general or efficient method was known to solve the problem. So optimum solutions (i.e., channel allocations) were obtained only with an exhaustive computer search [1].

However, the techniques [1,8–14] have the drawback of increased bandwidth requirement as compared to equally spaced channel allocation. This is due to the constraint that the minimum channel spacing between each channel and that the difference in the channel spacing between any two channels is assigned to be distinct. As the number of channels increases, the bandwidth for the unequally spaced channel allocation methods increases in proportion [4].

Optimal Golomb ruler (OGR) [7,15–17] has been proposed in literature for optimal channel allocation. This method for channel allocation achieves reduction in FWM crosstalk effect with the WDM systems without inducing additional cost in terms of bandwidth. This technique allows the gradual computation of a channel allocation set to result in an optimal point where degradation caused by inter-channel interference (ICI) and FWM is minimal [4,16].

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Much effort has been made to compute short or dense Golomb rulers and to prove them optimal. Golomb rulers represent a class of problems known as NP-complete [18]. Unlike the traveling salesman problem (TSP), which may be classified as a *complete ordered set*, the Golomb ruler may be classified as an *incomplete ordered set*. The exhaustive search [19,20], without heuristics, of such problems is impossible for higher order models. As marks are added to the ruler, the time required to search the permutations and to test the ruler increases exponentially. The success of soft computing approaches such as Genetic Algorithms (GAs) [21–23] in finding relatively good solutions to NP-complete problems provides a good starting point for methods of finding near-optimal Golomb ruler sequences. Hence, soft computing approaches seem to be very effective solutions for the NP-complete problems. No doubt, these approaches do not give the exact or best solutions but reasonably good solutions are available at a given cost. In this paper, a novel optimization algorithm based upon the theory of biogeography called Biogeography Based Optimization to generate the near-OGR sequences for various marks in reasonable time and its comparison with two conventional/classical approaches and Genetic Algorithm is being introduced.

The remainder of this paper is organized as follows: Section 2 introduces the concept of Golomb rulers. Section 3 presents the problem formulation. Section 4 briefly introduces two soft computing approaches, i.e., Genetic Algorithms and Biogeography Based Optimization. This section further presents steps to generate the near-optimal Golomb ruler sequences by using these soft computing approaches. Section 5 provides simulation results comparing with conventional/classical approaches of generating unequal channel spacing, i.e., Extended Quadratic Congruence (EQC) and Search Algorithm (SA). Section 6 presents some concluding remarks.

2. Golomb rulers

The idea of *Golomb rulers* was first introduced by Babcock [7] in 1952, and further derived in 1977 from the relevant work by Golomb et al. [15], a professor of mathematics and electrical engineering at the University of Southern California. According to Colannino [24] and Dimitromanolakis [25], Babcock [7] first discovered Golomb rulers up to 10-marks, while analyzing positioning of radio channels in the frequency spectrum. He investigated inter-modulation distortion appearing in consecutive radio bands and observed that when positioning each pair of channels at a distinct distance, then third order distortion was eliminated and fifth order distortion was lessened greatly. According to Rankin [26], all of rulers' up to eight are optimum, the nine and ten mark rulers that Babcock presents are near-optimum.

The term *Golomb ruler* refers to a set of non-negative integers such that no distinct pairs of numbers from the set have the same difference [27]. These numbers are referred to as *marks* [15,21,28] and correspond to positions on a linear scale. The difference between the values of any two marks is called the *distance* between those marks. The difference between the largest and smallest number is referred to as the *length* of the ruler. The number of marks on a ruler is sometimes referred to as the *size* of the ruler. Unlike usual rulers, Golomb rulers measure more discrete lengths than the number of marks they carry. Normally the first mark of the ruler [15,16,29] is set on position 0. Since the difference between any two numbers is distinct, the new FWM frequencies generated would not fall into the one already assigned for the carrier channels. Golomb rulers are not redundant as they do not measure the same distance twice [29].

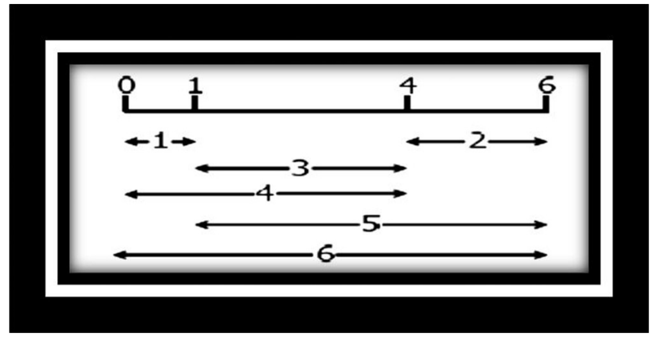

Fig. 1. A Golomb ruler with 4-marks and length 6.

Fig. 1 shows an example of Golomb ruler. The distance between each pair of marks is also shown in the figure [21].

The particularity of Golomb rulers is that all differences between pairs of marks are unique [29,30]. Although the definition of a Golomb ruler does not place any restriction on the length of the ruler, researchers are usually interested in rulers with minimum length.

A *perfect Golomb ruler* measures all the integer distances from 0 to L, where L is the length of the ruler [18,21,22]. In other words, the difference triangle of a perfect Golomb ruler contains all numbers between one and the length of the ruler. The length [31,32] of an n-mark perfect Golomb ruler should be at least $(1/2)n(n-1)$.

An *optimal Golomb ruler* is defined as the shortest length ruler for a given number of marks [21,33]. There can be multiple different OGRs for a specific number of marks.

For example, as shown in Fig. 2 the set (0, 1, 3, 7) is a non-optimal 4-mark Golomb ruler since its differences are ($1=1-0$, $2=3-1$, $3=3-0$, $4=7-3$, $6=7-1$, $7=7-0$), all of which are distinct. As from the differences it is clear that the number 5 is missing so it is not a perfect Golomb ruler sequence.

However, the unique optimal Golomb 4-mark ruler is (0, 1, 4, 6), which measures the distances (1, 2, 3, 4, 5, 6) (and is therefore also a perfect ruler) as shown in Fig. 1.

The OGRs are used in a variety of real-world applications including communications and radio astronomy, X-ray crystallography, coding theory, linear arrays, computer communication network, PPM communications, circuit layout, geographical mapping and self-orthogonal codes [7,15,21,22,26].

An n-mark Golomb ruler is a set of 'n' distinct nonnegative integers $(a_1, a_2, \ldots, a_n)$, called *marks*, such that the positive differences $|a_i - a_j|$, computed over all possible pairs of different integers $i, j = 1, 2, \ldots, n$ with $i \neq j$ are distinct [20]. Let a_n be the largest integer in an n-mark Golomb ruler [34]. Then an n-mark Golomb ruler $(0, \ldots, a_n)$ is said to be optimal if and only if

1. There exists no other n-mark Golomb rulers having smaller largest mark a_n, and

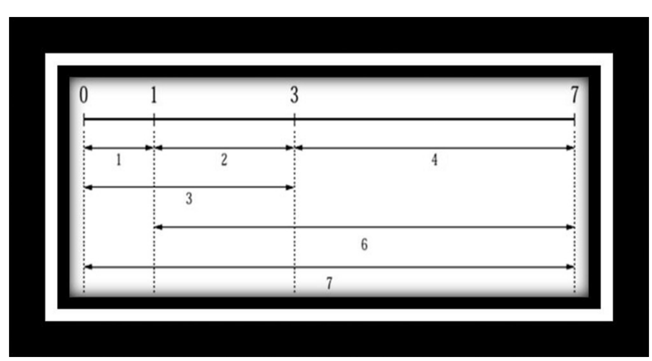

Fig. 2. An optimal Golomb ruler of 4-marks and length 7.