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Interference management techniques in cellular networks: A review

Y.A. Adediran[1], H. Lasisi[2*] and O.B. Okedere[3]

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*Corresponding author: H. Lasisi, Electrical and Electronics Engineering Department, Osun State University, Osogbo, Osun State, Nigeria
E-mail: lashammed@yahoo.com

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Kun Chen, Wuhan University of Technology, China

Additional information is available at the end of the article

Abstract: In modern times, communications technologies serve as the drivers of social, economic and political developments. But, interference in the communication networks comes as undesirable nuisance. In this work, techniques employed in the management of interference encountered in cellular networks are reviewed. Propositions by different Authors include intermodulation solutions, frequency planning methods, genetic algorithms, Simulated annealing models, ordering heuristic, ant colony and multi-agent optimization, artificial neural networks model, evolutionary strategy approach (EAs), and hybrid EAs. While many techniques work more effectively in some areas of operations, others show strong performances in other areas. For instance, the technique of weak cooperation among base station proposed by some authors offer significant network performance when employed as it provides framework for optimal performances of adjacent base stations under some performance objectives. Also evolutionary strategy approach employed by some other authors shows proficiency in the management of channels allocation aimed at minimizing the problems of interference, which can manifest as call blocking or dropping. Furthermore, some authors designed hybrid EAs integrating local search and constraint programming into evolutionary operators, which was shown to

ABOUT THE AUTHOR

H. Lasisi is a lecturer and researcher in the Department of Electrical and Electronics Engineering, Osun state University, Osogbo, Nigeria. He holds Master's degree in Electrical and Electronics Engineering from University of Ilorin, Nigeria. He is currently at advance stage on his PhD in the same University of Ilorin, with specialization in Telecommunication Engineering. He is a registered member of the Council for the Regulation of Engineering in Nigeria (COREN).

PUBLIC INTEREST STATEMENT

In modern times, communications technologies serve as the drivers of social, economic and political developments. But, interference in the communication networks comes as undesirable nuisance to the systems quality of service. In this work, techniques employed in the management of interference encountered in cellular networks are reviewed. Despite all efforts, challenges of interference still abound in communication networks. Among several techniques available to address interference networks, Evolutionary Algorithms have been given wider applications and the results show good performance of this technique. Meanwhile, genetic algorithm is also efficient where applied, but to reduce interference to the minimum in the current and future mobile communication networks, this review proposes and recommends synchronization of reduction techniques, where traffic-driven factors are considered. The actual public interest is that a reduced or coordinated interference ensures better quality of service to the network subscribers.

speed up performance. Despite all efforts, challenges of interference still abound in communication networks. Among several techniques available to address interference networks, EAs has been given wider applications and the results show good performance of this technique. Meanwhile, genetic algorithm is also efficient where applied, but to reduce interference to the minimum in the current and future mobile communication networks, this review proposes synchronization of reduction techniques, where traffic-driven factors are considered.

Subjects: Electrical & Electronic Engineering; Electromagnetics & Communication; Electronic Devices & Materials

Keywords: genetic algorithms; simulated annealing; ordering heuristic; ant colony; multi-agent optimization; neural networks; evolutionary algorithms

1. Introduction

Wireless communication is a system of communication that supports the transmission of information (voice, video, and data) over large distances using free space as the communication link. The term Global System for Mobile Communication (GSM) refers to a form of wireless communication involving a number of Mobile Users (MU) interacting with Base Stations (BS) to transmit and receive signal data in real time. Network service providers are licensed to operate on a designated spectrum to serve their subscribers. An allocated spectrum can be divided into a set of disjoint or non-interfering radio signal. Techniques such as frequency division (FD), Time Division (TD), and Code Division (CD) can be used to divide a radio spectrum into different channels.

In modern times, communications technologies serve as the drivers of social, economic and political developments. But, interference in the communication networks comes as undesirable nuisance which is limiting the benefits derivable from this important technology. Interference poses a major problem in GSM networks for service providers as it reduces the quality of service for service providers which may result in reduction in revenue. The common types of interference in cellular networks are: self-interference, multiple access interference, co-channel interference (CCI) and adjacent channel interference (ACI). Self-interference is induced by signals that are transmitted on a shared transmitter. Multiple access interference is induced by transmission from multiple radios using the same frequency resource. CCI occurs in links that re-use the same frequency channel. ACI is the interference induced between links that communicate in the same geographical location using neighboring frequency bands. A number of techniques have been proposed for mitigating interference in cellular networks. Common methods include; power control, effective frequency assignment using intelligent techniques and intermodulation solutions.

Several authors have addressed the problems of interference in the wireless networks. These authors proposed several techniques with the aim of addressing various aspects of interference. For example, Brehmer and Utschick (2010) propose weak cooperation as an interference management technique among BS in order to gain significant performance. Evolutionary strategy approach was employed by Vidyarthi, Ngom, and Stojmenovic (2005) to address the challenges in channels allocation aimed at minimizing the problems of interference, which can manifest as call blocking or dropping. Dorne and Jin-Kao Hao (1995) also employed evolutionary approach for the frequency assignment problem with the aim of minimizing interference in cellular network. The authors designed a hydrid EAs integrating local search, constraint programming, etc. into evolutionary operators, which was shown to speed up performance.

Despite the above, challenges of interference still abound in communications network. In this work, efforts are made to review interference management techniques that are available in open literature. This work presents these techniques in logical manner with a view to identify the strengths and weaknesses in each approach.

2. Interference types in cellular networks

The following types of inference may be associated with wireless networks; Self interference, multiple access interference, CCI, and ACI.

2.1. Self-interference

Self-interference is due to interference induced among signals that are transmitted from a shared transmitter. The amount of interference induced depends on the modulation type. In OFDM, self-interference among sub carriers due to carrier frequency offsets caused by oscillator mismatches, Doppler Effect and fast fading caused by motion of the transceivers. Transceiver non-idealities such as amplifier non-linearity and IQ imbalance may also be source self-interference. Interference between the uplink and downlink transmissions in a FD duplex system may be also classified as self-interference, as it occurs among signals send on the same two-way connection. This interference is mitigated by employing duplex filters. The impact of self-interference may be reduced by selecting the physical layer numerology such that the operating conditions and implementation technology are taken into account.

2.2. Multiple access interference

Multiple access interference refers to the interference induced among the transmission from multiple radios using the same frequency resource to a single receiver. In theory, the physical layer will allow orthogonal multiple accesses, however, factors such as synchronization errors, RF circuitry non-idealities, and the effect of wireless propagation channel will not allow orthogonality to be maintained in practice. An essential method of maintaining orthogonality in multiple access scenarios is power control.

2.3. Co-channel interference

CCI between links that reuse the same frequency band (channel). It is also referred to as inter-cell interference in cellular systems. The effect of CCI may be minimized by employing fixed frequency re-use patterns. Common methods for CCI management in cellular networks include: Frequency re-use, MIMO techniques, Interference alignment, and adaptation to interference variation. High frequency re-use factor implies a constant data rate across the service area (reference). This situation leads to similar throughput experience by users at different locations of the cell, and the service rate distribution.

Another method of dealing with CCI is by considering co-operation among transmitters. Such techniques have been investigated in the literature under the name of network MIMO (Gesbert et al., 2010; Huang, Lau, & Chen, 2009). In network MIMO, the interference channel is transformed to a broadcast channel by considering the co-operating transmitter as a single transmitter (Janis, 2013). Data traffic may be shared between multiple cooperating transmitters from which it may then be coherently transmitted to the destination receiver.

2.4. Adjacent channel interference

ACI is the interference induced between links that communicate in the same geographical location using neighboring frequency bands. A transmitter occupying a certain frequency band also leaks energy on frequency adjacent to that band. The out-of-band emissions are perceived as interference by other receivers. The effect of the out-of-band emissions may be quantified using the adjacent channel power ratio (ACPR).

Signals outside the nominal frequency band generate interference components on the in-band frequencies at the receiver. The adjacent channel sensitivity (ACS) determines the ability of the receiver to cope with an out-of-band interferer. The properties of the RF chain that contribute to ACS characteristics include; the quality of channel selection filters, analogue-to-digital converter bit width, and the linearity of amplifiers and mixers.

3. Interference reduction techniques

3.1. Intermodulation solutions

The amplitude modulation of signals containing two or more frequencies in a system with non-linearities is referred to as intermodulation. Intermodulation between constituent frequencies will result in additional signals at frequencies that are not just at harmonic frequencies of either, but also at the sum and difference frequencies of the original frequencies and at multiple of those sum and differences. The types of intermodulation of interest in co-located BS are; forward and reverse intermodulation (RIM). Forward intermodulation (FIM) components are induced in the victim receivers and are of major concern when they fall directly on the required signal. A knowledge-based filtering method was used in German, Annamalai, Young, and Miller (2010) to eliminate the FIM components. This method relies on the knowledge of co-located transceiver specifications and antenna configurations which makes it unsuitable for dynamic environments. Demirkiran, Weiner, Drozd, and Kasperovich (2010) described another approach that located the jamming signal by scanning the spectrum with Fast Fourier Transform (FFT) and then removed it with a tunable notch filter. The disadvantage of this approach is that it adds extra filter complexity issues and it does not help in mitigating the RIM distortions at the transmitter end.

Guthrie and Hanson (2005) proposed a solution that involved the placement of frequency agile band pass filter in front of receiver low noise amplifiers (LNAs) and after the transmitter power amplifiers (PAs) for a military frequency hopping communication system. This method stops large jamming signal through the receiver pre-filtering and admits only the desired signal into the LNA. The transmitter post-filtering blocks any reverse signal from entering the PA and stops IM products produced from being transmitted, however it is commercially unfeasible for wireless service providers because the frequency agility adds another dimension of complexity and overall cost (Ahmed & Faulkner, 2012).

The proposed solution for the FIM problem described by Ahmed and Faulkner (2012) is based on the concept of adaptive noise cancelling described in Widrow et al. (1975). The solution employs a primary input transducer to receive the noise corrupted desired signal and a reference transducer to acquire noise that has a correlation to the primary input's noise. The reference input is adaptively filtered and subtracted from the primary input to obtain the actual desired signal. The technique proposed by Ahmed and Faulkner (2011) for mitigating FIM products leverages from achieving a sufficiently large interference-to-signal ratio on the reference antenna by placing it close to the interfering jammer. This scheme achieves a jammer reduction of 48 dB. This solution also has the benefit of adapting to jamming signals over a wide range of frequencies.

RIM distortions are generated when high powered transmission from a jammer radiates into the antenna system of another jammer. These signals mix together in the non-linear output stage of the PA. The adaptive solution for RIM distortions are broadly classified into Transmitter-end Solutions and Interference Cancellation Using Regenerated Distortions. The traditional transmitter-end solution involves placement of multiple isolators at the PA output. This has the advantage of attenuating the reverse signal but it causes an insertion loss for the desired forward transmission. Katz, McGee, Brinton, and Qiu (2011) replace some of the isolators with a directional coupler and cancelling circuits. The scheme gave about 35 dB reduction in RIM, but the scheme requires cooperation between transmitter operators.

3.2. Frequency planning methods

Frequency (channel) allocation in cellular networks is an important subject amongst researchers, optimization engineers and mathematicians. The population of MU increases daily while available spectrum remains fixed. Hence, the frequency allocation problem is modeled as a multi-objective, multi-constraint optimization problem where given a number of BS and available channels it is required to find an optimal frequency plan that satisfy the channel demands of MU in a geographical area and the interference constraints. The common interference constraints in FAP problems are;

co-channel, co-site and adjacent channel constraints. The solution methods applied to FAP are classified into two; Optimization techniques and heuristic search techniques.

The various heuristic methods include; greedy algorithms (Adjakpl′e & Jaumard, 1997; Koller & Noble, 2004; Sivarajan, McEliece, & Ketchum, 1989; Zoeliner & Beall, 1977), local search (Box, 1978; Mishra, Banerjee, & Arbaugh, 2005; Papadimitriou & Steiglitz, 1982; Wei Wang & Rushforth, 1996), tabu search (Bouju et al., 1995; Costa, 1993; Hao & Perrier, 1999; Montemanni, Moon, & Smith, 2003), simulated annealing (Costa, 1993; Knalmann & Quellmalz, 1994; Quellmalz, Knalmann, & Muller, 1995), genetic algorithm (Dorne & Hao, 1996; Dorne & Jin-Kao Hao, 1995; Valenzuela, Hurley, & Smith, 1998), artificial neural networks (Funabiki & Takefuji, 1992; Kim, Park, Dowd, & Nasrabadi, 1996; Kunz, 1991; Smith & Palaniswami, 1997), ant colony and multi-agent optimization (Maniezzo & Carbonaro, 2000; Montemanni, Smith, & Allen, 2002).

3.3. Genetic algorithms

Evolutionary computation (EC) is a computational approach that models biological evolutionary principles to solve mathematical optimization problems. The field of evolutionary computation is sub-divided into; genetic algorithms, genetic programming, evolutionary strategies and evolutionary computation. EC draws mainly from the concept of biological genetics hence terminologies such as mutation, crossover, parent, chromosomes, genes, genome, selection etc. are used quantitatively to define processes involved in applying EC to optimization problems.

Numerous research papers have been developed to apply Genetic Algorithms (GA) to the channel assignment problem (GA). The problem formulation is often viewed thus; given *n* radio cells and a number of available channels, it is required to find an optimal channel assignment that minimizes the three interference constraints and maximizes resources and available spectrum. In genetic algorithms, a number of feasible solutions are usually randomly generated and these are denoted as parents at the initiation, new offspring are generated either using crossover or mutation operators. Cross-over operators perform the cross over between parents to exchange information form better offspring while mutation operators combine random mutagens with individual parents to form a new generation. This process is repeated iteratively until an optimal solution is found that satisfy a fitness function that evaluates the performance of the derived solution.

A novel approach is proposed in Vidyarthi et al. (2005) that combine fixed channel assignment (FCA) and dynamic channel assignment (DCA) to formulate the frequency assignment problem. The paper proposes a new distributed hybrid channel assignment strategy based on a fixed re-use distance. For a given cell, the neighbouring area is defined as all the cells which a located at a distance less than the re-use distance. The problem is formulated as assigning a channel to a new call at a particular cell with possible reassignment of on-going calls so as to maximize channel usage in that cell. In this study, the selection of a channel is subject to co-channel interference. Any other form in interference is neglected.

Upon the arrival of a new call, the cellular system looks for channels which are idle in the cell and its neighboring area (defined by the re-use distance). If no channel is found, the call is blocked; otherwise the ES algorithm finds a solution vector with minimum energy. This new vector includes channel for all the on-going calls and the new call. The proposed algorithm uses integers to model the solution vector and a fitness function was used to model soft constraints (packing condition, resonance condition and limitation of assignment operators). The energy fitness function is represented mathematically as,

$$E = -W_1 \sum_{j=1}^{d_k} \sum_{i=1}^{C} \sum_{i \neq k} A_{i,\, V_{k,j}} \cdot \frac{1}{\mathrm{dist}(i,\, k)} + W_2 \sum_{j=1}^{d_k} \sum_{i=1}^{C} \sum_{i \neq k} A_{i,\, V_{k,j}} \cdot \left(1 - \mathrm{res}(i,\, k)\right) - W_3 \sum_{j=1}^{d_k} A_{i,\, V_{k,j}} \tag{1}$$

The first, second and third term expresses the packing condition, resonance condition and limiting reassignment respectively. The fundamental characteristics of the model described are; infinite number of users, finite number of available channels, memory-less arrival of requests, call arrival which follows a Poisson distribution with a mean arrival rate of λ (calls/h), and call duration is exponential with mean $\varkappa$. The ES-based algorithm proposed was evaluated based on the call blocking probability for new calls. The blocking probability is the ratio between the new call clocked and the total number of call arrival in the system. The investigation of the use of recombination operator and implementation of genetic algorithm was cited as possible areas for future work.

The major drawbacks experienced in the application of genetic algorithms lie in its excessive time expended in finding a solution. Because the genetic algorithm is adapted to basically all optimization problems, researchers often apply a hybrid approach that combines other search techniques with GA to solve the channel assignment problem.

3.4. Simulated annealing

Simulated annealing is a local search technique that models the physical annealing process where a crystal is cooled from liquid state to solid state. The terminologies that define the processes in simulated annealing are; initial solution, temperature, cooling strategy and fitness function. The initial solution is a randomly generated solution that defines the start point of the search algorithm. The fitness function is a function that measures the effectiveness of a particular solution to the problem. The acceptance probability of a solution in the search space is controlled by the temperature while the cooling strategy defines how the algorithm explores the search space.

Duque-Anton, Kunz, and Ruber (1993) applied simulated annealing to the minimum interference frequency assignment problem (MI-FAP). A dummy frequency was introduced to serve (partially) an unsatisfied demand. The dummy frequency substitution implies increasing or decreasing the violation of traffic demand. The performance of the algorithm is increased; a new frequency is allocated dynamically as the most frequency assigned to close non-interfering matrices.

3.5. Ordering heuristic

Sivarajan et al. (1989) present an ordering heuristic that assigns degree to cells based on the cell's demand. The order of a cell is given according to the cell sequence in decreasing value of cell degree. The cell with a greater demand and inducing more significant EMC constraints is considered for channel assignment earlier. The cell degree is defined mathematically as

$$\delta_i = \sum_{j=1}^{n} d_j x_{ij} - c_{ii} \tag{2}$$

where δi = cell degree, d_j = cell degree, c_{ij} = cell demand, $c_{ij} - c_{ii}$ represents the interference constraints.

The ordering heuristic is of more importance in dynamic channel allocation (DCA) schemes where cell demand varies in real-time.

3.6. Ant colony and multi-agent optimization

The term "swarm intelligence" was first used by Beni and Wang (1993) to refer to the collective behavior of decentralized, self-organizing systems, artificial or natural interacting locally with their environment thereby causing a coherent functional global pattern to emerge.

Ant-colony optimization algorithms are mathematical algorithms that mimic the behavior of ants when searching for food. Mathematicians and optimization enthusiasts model the intelligent behavior of ants when searching for an optimal path between food source and their nest while relying on feedback from their environment through the deposition of pheromones along possible paths to a potential food source.

The application of ACO algorithms to channel assignment problems is gaining momentum. ACO is applicable to optimization problems that can be represented by a graph. The channel assignment problem is formulated thus; given n radio cells, a graph $G = [S, E]$ can be constructed to represent the problem domain where S represents the set of all radio cells and E is the set of edges connecting any pair of cells. A major advantage of this approach to frequency assignment problems lies in its responsiveness and adaptation to changing traffic conditions and network performance.

A hybrid ant colony optimization (ACO) strategy was employed by Yin and Li (2007). The problem formulation used in the research consider all the three electromagnetic compatibility (EMC) constraints; co-cell, co-channel and adjacent channel. The hybrid approach used combines the ordering technique and a local optimizer to enhance the performance of ACO on channel assignment problems. The local optimizer performs the selection of certain allocated channels and replaces them with the best available channels under the EMC constraints (Yin & Li, 2007). The HACO was evaluated on benchmark (Philadelphia) instances. Of eight testing problem instances, their algorithm was able to obtain optimal solutions for six instances and near-optimal solutions for two instances known in literature to be difficult. Yin and Li (2007) expressed that their HACO embeds problem dependent heuristics, which is more effective at handling the EMC constraints. Furthermore, the problem-embedded heuristics serve as intensification strategies conducted by the meta-heuristic framework and help improve the generated solutions constraints (Yin & Li, 2007).

3.7. Artificial neural networks

The term "Artificial Neural Networks" is used to refer to artificial systems that draw inspiration from the method of information processing by the biological neural networks. Analogues such as neurons, axons, dendrites, synapses etc. are used to model a computational information processing system. The computational mechanism used in ANN is known as learning. Two types of learning are prominent in ANN; supervised and unsupervised learning. In supervised learning, the neural network performs computation by mapping information from previous data (presented to the network) about the particular system under consideration. Unsupervised learning projects data about a system onto an N-dimensional space using neurons to represent the different data elements.

For spectrum allocation, the unsupervised learning approach is usually applied. A neuron represents a cell and it contains information about the cell demand and the cell frequencies. The neurons in the network are interconnected by a mathematical (energy) function such that the interference constraints and demand constraints are embedded. The learning process here runs iteratively until a minimum value of the energy function is achieved.

The FAP problem is defined in neural network thus; Associate a neuron V_{if} with each pair (i, f) where $i \in V$ and $f \in F(v)$ Two neurons are coupled if the corresponding vertices are adjacent in the interference graph. The energy function is the weighted sum of several terms, representing different types of interference constraints (co-cell, co-site etc.), demand constraints (number of required frequencies) and sometimes instance specific requirements.

Kim et al. (1996) assigns only binary values to the neurons. The energy function considers the several types of interference constraints and the level of unsatisfied demand. The level of unsatisfied demand is translated into an additional input to each neuron which forces the assignment of new frequencies to vertices with unsatisfied demand. In Smith and Palaniswami (1997), the Hop field network is modified to incorporate a hill climbing mechanism for escaping from local minima. The Hopfield network was reported to perform better than the self-organizing neural network.

4. Current and future challenges

The above review shows that numerous techniques are available for addressing the problems of interference in cellular networks. While many of these techniques seem to work more effectively in some areas of operations, others show strong applications in other areas. However, challenges abound in current situation as some of these techniques have not been given field applications.

Table 1. Summary of interference management techniques reviewed

Interference management techniques	Strength	Limitation
Intermodulation solutions		
Knowledge-based filtering method	Appreciable level of interference reduction was achieved	Had extra filter complexities
Interference signal scanning and removal with FFT and notch filter respectively	Appreciable level of interference reduction was achieved	Had extra filter complexities and RIM distortions are not mitigated
Placement of frequency agile band pass filters in front of receiver and after transmitter	Appreciable level of interference reduction was achieved	Commercially unfeasible as frequency agility adds another dimension of complexities and overall cost
Adaptive noise/interference cancellation	Appreciable level of interference reduction was achieved	Requires high level of cooperation between transmitter operators
Frequency planning		
Genetic algorithm	Appreciable level of interference reduction was achieved	Excessive time is expended in finding a solution
Simulated annealing	Appreciable level of interference reduction was achieved	Introduction of dummy frequency increases violation of traffic demand
Ordering heuristic	It offers advantages in dynamic cell allocation schemes where cell demand varies in real time	Less considered for static channel allocation schemes
Ant-colony and multi-agent optimization	It is more effective at handling electromagnetic compatibility constraints and helps improve the generated solutions	Optimal solutions are difficult in some instances
Artificial neural networks	Appreciable level of interference reduction was achieved	The technique may involve high computational complexity

Table 1 summarizes the strengths and limitations of the various interference management techniques reviewed in this paper.

5. Concluding remarks

Among several techniques available to address interference networks, EAs has been given wider applications and the results show good performance of this technique. Meanwhile, genetic algorithm is also efficient where applied, but to take interference in current and future mobile communication network deployment under bearable check, synchronization of reduction techniques where traffic driven factors such as war and population drift are considered may be the best.

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Author details
Y.A. Adediran[1]
E-mail: yinusaade2012@gmail.com
H. Lasisi[2]
E-mail: lashammed@yahoo.com
O.B. Okedere[3]
E-mail: tunjiokedere@gmail.com
[1] Electrical and Electronics Engineering Department, University of Ilorin, Ilorin, Kwara State, Nigeria.
[2] Electrical and Electronics Engineering Department, Osun State University, Osogbo, Osun State, Nigeria.
[3] Faculty of Engineering Department, Osun State University, Osogbo, Osun State, Nigeria.

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