EVOLUTION STRATEGY FOR COLLABORATIVE BEAMFORMING IN WIRELESS SENSOR NETWORKS

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ABSTRACT

EVOLUTION STRATEGY FOR COLLABORATIVE BEAMFORMING IN WIRELESS SENSOR NETWORKS

The aim of this research is to improve the efficiency of the phase synchronisation algorithm in order to achieve collaborative beamforming (CB) in wireless sensor networks (WSNs). Generally, CB uses a group of distributed wireless sensor nodes, which collectively transmit a common message with different proper weights to an intended location. This group of distributed wireless sensor nodes intrinsically act as a set of virtual antenna array and inherit the natural highly directional transmission properties from conventional antenna array. However, distinct of conventional antenna array, each sensor node in CB has an independent local oscillator. It becomes a vital problem to achieve CB as the distributed sensor nodes are unaware of their phase relationship. An iterative algorithm using evolution strategy (ES) is proposed to achieve phase alignment at the intended location in static channels, which require one-bit feedback from the receiver destination. By implementing ES in phase synchronisation, each sensor node independently adjusts its phase perturbation size accordingly to speed up the phase synchronisation. Evaluations have been carried out through simulation and result show that the performance using ES is improved by 18.7 % convergence speed as compared to the conventional one-bit feedback (C1BF) approach. In addition, inverse phase perturbation is introduced for the improved ES (IES) which further improved the convergence speed by 31.6 % over the C1BF approach. Adaptive-IES is proposed for time-varying channels and the results show that the Adaptive-IES has the ability to detect channel changes. Therefore, it can be concluded that the proposed algorithm is robust in practical implementation.

ABSTRAK

Maklamat kajian ini adalah untuk meningkatkan kecekapan algoritma penyegerakan fasa pembawa dalam usaha untuk mencapai kerjasama "beamforming" (CB) dalam rangkaian sensor tanpa wayar (WSNs). Secara umumnya, CB menggunakan sekumpulan nod sensor tanpa wayar yang teragih dan menghantar mesej yang sama dengan berat fasa yang sesuai secara kolektif ke lokasi yang dikehendaki. Kumpulan nod sensor tanpa wayar yang teragih tersebut secara intrinsik bertindak sebagai satu set tatasusunan antena maya dan mempunyai sifat-sifat transmisi semulajadi dari tatasusunan antena konvensional iaitu perambatan transmisi yang amat berarah. Walau bagaimanapun, berbeza daripada tatasusunan antena konvensional, setiap nod sensor dalam CB mempunyai pengayun tempatan tersendiri. Ia merupakan satu masalah untuk mencapai kerjasama "beamforming" bagi nod sensor yang teragih apabila nod sensor tersebut tidak menyedari hubungan fasa antara nod sensor yang lain. Lelaran algoritma menggunakan evolusi strategi (ES) dicadangkan untuk mencapai fasa pembawa yang selaras di lokasi yang dicadangkan dalam keadaan saluran yang statik dengan hanya menggunakan maklum balas satu bit dari destinasi penerima. Dengan pembenaman ES dalam algoritma pembawa penyegerakan fasa pembawa, setiap nod sensor bertindak secara berasingan untuk menyesuaikan saiz pengusi fasa sendiri dengan sewajarnya. Simulasi ES telah menunjukkan peningkatan 18.7 % kelajuan penumpuan berbanding dengan penyelesaian konvensional. Tambahan itu, peningkatan sebanyak 31.6 % kelajuan penumpuan telah ditunjukkan melalui pengenalan pengusikan fasa songsang dalam algoritma peningkat ES (IES). Adaptive-IES dicadangkan untuk mengesan pengubahan saluran masa and keputusan menunjukkan pengukuhan algoritma Adaptive-IES kepada pengubahan saluran masa. Kesimpulannya, algoritma yang dicadangkan adalah lebih teguh dalam perlaksanaan praktikal.

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LIST OF ABBREVIATIONS

ADC	Analog-to-Digital
AOA	Angle of Arrival
AP	Access Point
BER	Bit Error Rate
BS	Base Station
C1BF	Conventional One-Bit Feedback
CB	Collaborative Beamforming
CC	Cooperative Communication
COTS	Common Off-The-Shelf
CPU	Central Processing Unit
CSI	Channel State Information
DARPA	Defence Advanced Research Project Agency
DSN	Distributed Sensor Network
EA	Evolutionary Algorithm
ES	Evolution Strategy
GSM	Global System for Mobile Communication
I/O	Input and Output
IC	Integrated Circuit
LO	Local Oscillator
LOS	Line-of-sight
MIMO	Multiple Input Multiple Output
ODE	Ordinary Differential Equation
PLLs	Phase-Locked Loops
PPM	Parts per Million

RF	Radio Frequency
RSS	Received Signal Strength
SNR	Signal Noise Ratio
TPC	Transmission Power Control
ULA	Uniform Linear Array
WSNs	Wireless Sensor Networks

LIST OF SYMBOLS

a	Signal Amplitude
AF	Array Factor
β	Phase Drift Speed
c	Speed of Light
C	Mutation Factor
C_{se}	Small Exploration Factor
C_{le}	Large Exploration Factor
d	Distance between Sensor Node
d_F	Fix Distance
δ	Random Phase Perturbation Step Size
δ_0	Initial Random Phase Perturbation Step Size
$\delta_i[n]$	Random Phase Perturbation Step Size for i_{th} Sensor Node in Time Slot n
$\Delta\varphi$	Phase Difference of the Electromagnetic Waves Signal
$\Delta\varphi_i[n]$	Phase Difference of the Electromagnetic Waves Signal From i_{th} Sensor Node in Time Slot n
$\emptyset_i$	Carrier Phase for Beamforming at i_{th} Sensor Node
E_c	Estimation between Current and Maximum Received Signal Strength
E_p	Estimation between History and Maximum Received Signal Strength.
f_c	Carrier Frequency
G	Beamforming Gain
γ_i	Phase Offset For i_{th} Sensor Node
h_i	Channel Coefficient from i_{th} Sensor Node
$\mathrm{H}(f)$	Channel Model

i	Sensor Node Number
λ	Wavelength
m	Number Iteration for Successful Probability
$m(t)$	Message Signal
μ	Mean
n	Time Slot
$n(t)$	Additive White Gaussian Noise
$nRSS[n]$	Normalised Received Signal Strength in Time Slot n
N	Number of Collaborative Sensor Node
$\sim N$	Gaussian Distribution Function
θ	Elevation Angle
θ_a	Angle of Arrival
(θ_0, ϕ_0)	Direction of Signal Source toward Base Station
(θ_a, ϕ_a)	Direction of Signal Source
Φ_{i}	Total Phase Component from i_{th} Sensor Node at Base Station
$\Phi_{\mathrm{i}}[n]$	Total Phase Component from i_{th} Sensor Node at Base Station in Time Slot n
ω_c	Carrier Frequency in Radian
ϕ	Azimuth Angle
$\psi_i[n]$	Channel Phase response of i_{th} Sensor Node in Time Slot n
$\mathrm{P}_{\mathrm{offset}}$	Total Phase Offset
P_r	Success Rule Probability
P_s	Successful Probability
ψ_i	Channel Phase Response i_{th} Sensor Node
$r(t)$	Received Signal

R	Disk Radius
$R_{i,0}$	Euclidean Distance between i_{th} Sensor Node and Base Station
RSS	Received Signal Strength
$RSS\ [n]$	Received Signal Strength in Time Slot n
RSS_{accept}	Acceptable Received Signal Strength Threshold for Collaborative Beamforming
$RSS_{best}[n]$	Best Received Signal Strength in Time Slot n
$RSS_{history}[n]$	Received Signal Strength in History Stored at Time Slot n
$\Re$	Real Part Operator
$s(t)$	Source Signal
σ	Standard Deviation
$\Delta\tau$	Relative Time Delay
t	Time
φ	Initial Weighting Phase
φ_i	Adaptive Phase Component of i_{th} Sensor Node
$\varphi_i[n]$	Adaptive Phase Component of i_{th} Sensor Node in Time Slot n
w	Weighting Function
(x_i, y_i, z_i)	Position of i_{th} Sensor Node in Cartesian Coordinate
X	Parent Solution
X_0	Initial Solution
$\tilde{X}_g$	Offspring Solution

CHAPTER 1

INTRODUCTION

1.1 Early Wireless and Wireless Sensor Networks

Wireless information transmitting systems existed long ago even before the advent of the Industrial Revolution (Seymour and Shaheen, 2011). These systems transmitted signals in line-of-sight (LOS) distances and using non-electric methods such as smoke signal, semaphore flags, and flashing mirrors. However, these communication systems were replaced by the invention of telegraph network, which uses electrical circuits. Later, it was replaced by the inventions of the telephone, followed by radio transmission.

Distinct from these early wireless communication inventions, ALOHANET was developed at the University of Hawaii, which is the first packet based network that soon becomes the well-known global Internet (Sarkar *et al.*, 2006). The success of ALOHANET is a very important encouragement to the US government agency or Defence Advanced Research Project Agency (DARPA). By using the same principle, DARPA carried out a series of research for tactical communications network in the battlefield called Distributed Sensor Network (DSN). However, development of a small and powerful sensor node is a very challenging task during that time due to technology limitations.

Recent advances in sensing, wireless digital communication, integrated circuit (IC) and microelectronics technology have permitted the development of lightweight, relatively inexpensive, low power and multifunctional miniature sensor nodes (Akyildiz *et al.*, 2002a, 2002b). These sensor nodes are capable of collecting information about the physical environment, coordinate with each other, and communicate wirelessly by forming a network. Each sensor node is equipped with a processing unit, a sensing unit, a communication unit, and a power unit. This advance technology led to the birth of the Wireless Sensor Networks (WSNs).

WSNs has been announced as one of the ten emerging technologies that will change the world (Technology Review, 2003). It is believed to change the way human live and interact with the physical world (Zheng and Jamalipour, 2009). It has attracted much research attention and has proven as a key research topic in recent years (Chong and Kumar, 2003; Yick *et al.*, 2008; and Lotf *et al.*, 2011). The number of potential applications in WSNs is growing rapidly due to the wide range and flexibility of WSNs (Culler *et al.*, 2004 and Zhao and Guibas, 2004).

Typically, sensor nodes are deployed in the sensing area for continuous data collecting and environment monitoring. In some of the WSNs applications, the sensing data must be transmitted to the base station (BS) in order to allow the end-user data access. For some cases, the distance between BS and the sensing area might be too far. Traditional transmission techniques such as direct transmission and multi-hop transmission, which are used for the network communication, have limited communication ranges and are inapplicable due to limited power supply and the effect of path loss in wireless transmission. Moreover, among the sensor node functions, long distance transmission is major energy consumer. Therefore, proper design of signal processing and networking operations are essential for prolonging the operation lifetime of the sensor node.

1.2 Collaborative Beamforming in Wireless Sensor Network

Beamforming is a signal processing technique generally used in antenna array to control the directional of the signal transmission. Beamforming technique combining transmitted signals from the antenna array to created constructive interferences at the intended direction. As a result, the signal strength is significantly increased. Beamforming can be used to boost the communication range by providing a higher signal to noise ratio (SNR) and received signal strength (RSS).

Collaborative beamforming (CB), also referred as distributed beamforming, is the idea that beamforming concept is used to establish the communication link in WSNs. In CB, a group of sensor nodes intrinsically act as a set of a virtual antenna array. CB considers isotopic antenna of the sensor nodes as elements of an antenna array. All sensor nodes shared the same common message. Each of the sensor nodes employs a proper phase and the messages are synchronously transmitted towards the intended direction.

Due to high SNR and RSS of beamforming, CB can transmit signal over long communication distance (Uher *et al.*, 2011). Compared with direct transmission using single sensor node or multi-hop transmissions, CB distributes the energy consumption over multiple sensor nodes (Betz *et al.*, 2007). Therefore, individual sensor node uses less energy for transmission. CB balances the energy consumption throughout the network, Hence, prolonging the network lifetime.

Although CB has such unique benefits on WSNs, the implementation of CB is not straight forward. The principle challenge of realizing CB in practice is to synchronise the signal phase of individual sensor nodes in such a way that the signal combine coherently at the intended destination (Mudumbai *et al.,* 2009). Distinct from centralised beamforming, each sensor node has an independent local oscillator (LO) that is used to generate the carrier signal. The signals produced from different LO are catastrophic for CB since the phase of the signals may not be synchronised and may even result in destructive combing at the intended destination.

The knowledge of channel state information (CSI) is the factor that decides the performance of the CB. Perfect CSI is needed to obtain phase setting for each sensor node and achieve phase synchronisation at the desired destination. However, this knowledge is generally not available at sensor node. Obtaining perfect CSI at the sensor node side may be too expensive to acquire (Lin *et al.*, 2010). Therefore, phase synchronisation method without CSI is recommended.

A low-rate feedback link from the receiver can be used to make partial CSI available to the sensor node. Mudumbai *et al.* (2006) proposed a simple phase synchronisation algorithm that requires only one-bit feedback from the receiver. The authors proposed adjusting phase setting iteratively at the sensor nodes. Phase synchronisation at the receiver can be achieved after a large iteration. In this algorithm, all sensor nodes has an added a random perturbation on its phase offset in each iteration. Positive feedback is broadcasted to sensor nodes, if perturbation results in bigger RSS at the receiver, and the phase setting will be adopted. Otherwise, the added phase perturbation will be discarded.

There are two key advantages of this algorithm. Firstly, the algorithm does not require CSI and only rely on one-bit feedback. Secondly, it is simple in implementation and is scalability to a large number of sensor nodes. The shortcoming of the algorithm is that the algorithm takes a large number of iterations to achieve convergence. Energy-efficiency is a major concern in WSNs and radio transmission is one of the most energy consuming operation (Podpora *et al.*, 2008). Therefore, it is desirable to improve the convergence speed of the algorithm without sacrificing much on its key advantages.

In summary, the challenge ahead is to discover a new phase synchronisation algorithm that can improve the convergence speed of the phase synchronisation. In this work, evolution strategy (ES) is selected to improve the phase synchronisation performance. Compared to other evolutionary algorithms, the main advantage of ES is the use of strategy parameters, which can represent a preferred direction and step size for a further search. With this ability, it can be implemented on the sensor nodes to adjust the step size of phase perturbation in iteration. ES can search through large phase setting solution space for the maximum RSS.

1.3 Scope of Work

The primarily concern of this research is on the implementation of ES for phase synchronisation in order to achieve CB in WSNs. ES will be used as the phase synchronisation algorithm. The CB is modelled using geometrical model, channel model, phase offset model and RSS. CB model emulates the signal transmission of CB between sensor nodes and receiver. The model of CB is then used as the system model for phase synchronisation. Several prior conditions and assumptions of CB must be described. The sensor nodes are assumed randomly deployed in an area with four metres of distributed radius. The sensor nodes are assumed static in the network. All sensor nodes are equipped with an isotropic antenna, and CSI is unavailable. Sensor nodes are assumed locked with same carrier frequency. Therefore, the frequency drift is considered negligible. The carrier frequency used for the signal transmission is of 2.4GHz with unity signal amplitude. Sensor nodes are assumed sharing a common time reference and message. Phase synchronisation algorithm is simulated using the system model for phase synchronisation. ES is selected to improve the convergence speed of phase synchronisation. ES is designed to control the phase perturbation step size for sensor nodes by balance between exploration and exploitation to achieve fast convergence phase synchronisation.

1.4 Research Objectives

The aim of this research is to design a phase synchronisation algorithm which can improve the performance of phase synchronisation in order to perform CB. Effective phase synchronisation can be achieved through proper phase setting among sensor nodes. Phase synchronisation algorithm is implemented into the system model for phase synchronisation. ES is implementing in phase synchronisation for better control of the phase perturbation step size. Hence, ES provides better trade-off in problem space exploration and exploitation. The implementation of ES in phase synchronisation is tested in various simulations to investigate the behaviour and characteristic on phase convergence capability. The research objective can be achieved through the following objectives:

1.4.1 To Model and Simulate Collaborative Beamforming in Wireless Sensor Networks

The CB model is modelled by including geometrical model, channel model, phase offset model and RSS. These models can link more closely to the environment of CB in WSNs. The model is constructed and written in MATLAB m-file coding. Conventional phase synchronisation algorithm is simulated under the developed model. The development model and the algorithm is used as s benchmark for the performance analysis in the thesis.