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論文題目	FACTOR GRAPH-BASED GEOLOCATION TECHNIQUES FOR POSITION DETECTION OF UNKNOWN RADIO WAVE EMITTERS (ファクターグラフを用いた未知の電波発信源位置検出技術)		
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## 論文の内容の要旨

Wireless geolocation techniques are of crucial importance for current and future dense wireless networks to support location-based services and applications requiring high accuracy. One of the challenging problems in wireless geolocation is to estimate the position of an unknown (anonymous) radio wave emitter. The location detection of unknown radio emitter is very important especially for helping people in disastrous situations; such as, finding the victims who are buried due to landslide, tsunami, and/or earthquake. It is also important for monitoring illegal radio emitter to prevent public broadcasting from being jammed.

In this research, factor graph-based techniques for geolocation techniques are considered the most promising candidates having several benefits; namely, (i) it decomposes the complex problem with many variables into a set of simple sub-problems with fewer variables, (ii) it operates in the form of mean and variance messages under the Gaussianity assumption of the measurement error, and (iii) it also requires only solving linear equations resulting significant reduction in computational complexity. It should be noticed that low computational complexity is of great importance for green technology to save the energy consumption. Furthermore, high accuracy is achieved by the factor graph because it effectively and efficiently performs statistical signal processing for probability marginalization.

The primary objective of this research is to propose novel algorithms of high accuracy and low complexity wireless geolocation techniques, based on the factor graph technique, to detect non-moving (static) position of a single unknown (anonymous) radio wave emitter. However, it should be emphasized

that the proposed technique is not only applicable for unknown radio wave emitter, but also for general radio wave emitter position detections. In this research, three propagation parameters, i.e., direction of arrival (DOA), time difference of arrival (TDOA), and differential received signal strength (DRSS) are proposed, and their corresponding factor graph geolocation techniques are derived. Those techniques are suitable for solving the problems arising in each scenario for detecting the static position of single radio wave emitter.

In the presence of imperfect time synchronization with line-of-sight (LOS) condition, the DOA-based geolocation technique is known to be the best solution to the single static location detection. We consider factor graph geolocation technique, where the input is the samples of DOA measurement results sent from the sensors. This research proposes DOA-based factor graph (DOA-FG) with linear approximation of the tangent function so-called Taylor series DOA-FG (TS-DOA-FG), where the first order Taylor series expansion of the tangent is taken into account. It is shown that the accuracy of the DOA-FG geolocation algorithm can be improved by introducing approximated expressions for the mean and variance of the tangent and cotangent functions.

The TDOA-based geolocation techniques are known to be the most suitable solution in the presence of perfect time synchronization among the sensors. The proposed new technique, so-called Pythagorean TDOA-based factor graph (P-TDOA-FG), requires much less computational complexity compared to the conventional TDOA-based factor graph techniques employing hyperbolic function (H-TDOA-FG). The great improvement is due to the use of simple Pythagorean function, which is widely used in TOA-based geolocation techniques. The function is considered for the use of the conventional time of arrival (TOA)-based factor graph technique (TOA-FG). However, in practice, it is impossible for the TOA-based location identification techniques including the conventional TOA-FG to detect the position of the unknown target. This is because the TOA measurements require the knowledge of the absolute departure time of the signal, and this knowledge is unavailable.

The proposed P-TDOA-FG introduces several sets of new nodes and expressions into the conventional TOA-FG technique to convert the TDOA information from the measurements to the equivalent TOA information. The TDOA measurements do not require the knowledge of the absolute departure time information of the measured signal sent from the target. Hence, the equivalent TOA can be utilized in the modified TOA-FG to detect the position of the unknown target. The results have shown that the proposed P-TDOA-FG improves the accuracy of the conventional TOA-FG technique.

On the other hand, neither RSS-based nor DRSS-based geolocation techniques require the perfect time synchronization among the sensors and as well as between the target and sensors, array antenna, and knowledge of the absolute departure time of the signal sent from the target. In such conditions, the RSS

and DRSS-based geolocation techniques are believed to be the most promising solution for the geolocation detection. However, the conventional RSS-based factor graph (RSS-FG) technique can not estimate the position of an unknown radio emitter because the technique requires the knowledge of the absolute value of the transmit power. Nevertheless, in practice, the transmit power information from the signal transmitted by the unknown target emitter is unavailable. It should be noticed that the knowledge of the transmit power is necessary for calibration/reference of linear approximation process using training signal sent from the monitoring spots. Thus, the DRSS-based factor graph (DRSS-FG) technique is proposed to solve the problem, where the necessity for the knowledge of the absolute transmit power of unknown target is eliminated. Hence, the DRSS-FG can estimate the unknown target.

Closed-form expression of the Cramer Rao lower bound (CRLB) taking into account of the number of samples, for DOA- and TOA- geolocation techniques, are also derived in this dissertation. An approximated CRLB taking into account of the number of samples, for TDOA-based technique, is also derived. The performance of the proposed technique is evaluated in terms of root-mean-square error (RMSE). The results show that the proposed techniques accurately estimate the location of unknown target, while they requires low computational complexity. It is shown that all of our proposed techniques achieve much higher accuracy compared to the conventional techniques. The achieved RMSE with the proposed techniques are also evaluated and found to be very close to the CRLB.

Keywords: Wireless Geolocation, Factor Graphs, DOA, TDOA, DRSS, TOA, RSS, CRLB, Voronoi Diagram, Unknown Radio Wave Emitter, Single Static Target

## 論文審査の結果の要旨

本学位論文は未知違法電波発射源を、様々なワイヤレス電波伝搬パラメータの観測値をよって明らかにするための技術基盤の確立とアルゴリズム開発であり、従来から知られた方法と比較して大幅な推定精度向上が要求される。具体的な応用は、2020年東京オリンピック等の大規模イベントにおける危機管理のための違法電波監視アルゴリズム開発であり、安心安全な社会構築に寄与する。

従来から未知電波発射源探知アルゴリズムは演算量が多く実時間処理に向かない、装置規模が大きくなる、などの欠点があった。本学位論文はこの問題に対して、複雑な演算処理を簡便な演算ブロックの積にファクター分割し、それらの演算ブロック内で求められる未知電波発射源に関する情報をファクターグラフ上で交換しながら更新することで、繰り返し毎に演算精度が向上させ最終的に事後確率を最大とする推定位置に収束させる。電波伝搬環境に応じて優位性が異なるいくつかの伝搬パラメータを用い、かつ、それらをハイブリッド結合することで、従来から知ら

れた方法と比較して大幅な推定精度向上を可能とした。また、各種伝搬パラメータを用いた推定精度の理論限界である Cramer Rao Bound (CRB)を導出し、提案するアルゴリズムによる推定精度の Root Mean Square Error (RMSE) が理論限界である CRB を漸近的に達成することを示している。繰り返しアルゴリズム実行のための演算量が極めて少ないことが特徴で、大規模な装置を必要としない。

審査会は、Skype 会議システムと電話回線を併用することで、会場と、外国人審査委員及び国内からの遠隔参加審査委員がお互いを見ることが出来る環境下で進められた。当該研究室で定められたプロトコルに従って、章毎に審査委員が質問を行う形式の審査会で極めて厳格に行われた。本学位論文の骨格を成す部分は全て関連分野のトップジャーナルで出版決定(International Journal of Simulation: Systems, Science and Technology (IJSSST) 1 本)、及び条件付き採録(EURASIP Journal on Wireless Communications and Networking (JWCN)1 本)されている。また、国際会議でも 3 本の筆頭著者論文を発表し、そのうちの一つは最優秀論文賞を受賞した。審査委員の評価にも明記されるように、審査委員からも高い評価(審査委員 2 が A 評価、審査委員 3 が B 評価)を得た。以上、述べたように本論文は、学術的に貢献するところが大きい。よって博士(情報科学)の学位論文として十分価値あるものと認めた。