

Technique for order performance by similarity to ideal solution for solving complex situations in multi-criteria optimization of the tracking channels of GPS baseband telecommunication receivers

F. M. Jumaah¹ · A. A. Zaidan² · B. B. Zaidan² · R. Bahbib² · M. Y. Qahtan² · A. Sali¹

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Abstract Global positioning system (GPS) has undergone intensive development, starting as an advanced specialized tool to a general-purpose gadget used in our daily lives. GPS exists in new technologies, applications, and consumer products, especially in smartphones and tablets. In a GPS receiver design, power consumption and localization accuracy are critical factors that affect the outcome of a GPS receiver system. Theoretically, increasing the number of required tracking channels in a GPS baseband receiver increases the design complexity and size of this system. Thus, power consumption can significantly increase. The receiver should acquire and track numerous satellites to improve the location accuracy of a position, thereby indicating that the receiver requires a high number of tracking channels. Thus, optimizing these tracking channels to balance the conflict among performance parameters is a difficult and challenging task. This paper presents a technique for order performance by

similarity to ideal solution (TOPSIS) for solving complex situations for multi-criteria optimization of the tracking channels of GPS baseband telecommunication receiver. Nine operation modes of GPS receiver were evaluated by each design parameter, such as power consumption, localization accuracy, and time with no position available for static and dynamic positioning. Then, the TOPSIS was utilized and implemented to measure and rank the overall performance of tracking channel selection. Results of this study indicate that (1) multi-objective optimization is a reliable strategy for visualizing the trade-off among the GPS design parameters and providing a dynamic power consumption planning. (2) The best aggregated performance of the GPS receiver occurs when the number of tracking channels equals five and six for static and dynamic positioning, respectively. (3) The most frequent number of available satellites is eight, whereas the other number of satellites is a rare case to acquire. However, GPS standards require that available GPS satellites are constantly 12 at any time and place.

✉ A. A. Zaidan
aws.alaa@gmail.com; aws.alaa@fskik.upsi.edu.my

F. M. Jumaah
fawaz.technology@gmail.com

B. B. Zaidan
bilalbahaa@fskik.upsi.edu.my

R. Bahbib
bahbib@fskik.upsi.edu.my

M. Y. Qahtan
yahoophd@gmail.com

A. Sali
aduwati@upm.edu.my

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1 Introduction

Global positioning system (GPS) is a satellite-based navigation system developed and launched by the US Department of Defense (DoD) in 1978 and is officially called the navigation satellite timing and ranging (NAVSTAR) [5,14]. NAVSTAR is a key system in the new global navigation satellite system (GNSS) family, which combines GPS, GLONASS, BeiDou, and Galileo navigation systems [38]. GPS consists of 32 primary orbiting satellites [64]. Each satellite transmits direct-sequence spread spectrum code division multiple

¹ Electronics Engineering, University Putra Malaysia, Serdang, Malaysia

² Department of Computing, Faculty of Arts, Computing and Creative Industry, Universiti Pendidikan Sultan Idris, Tanjung Malim, Malaysia

access signals that are used by GPS receivers to perform calculations of time of arrival and position coordinates [8]. GPS has become an indispensable tool in navigation worldwide because it is a fully functioning GNSS [2]. Moreover, GPS provides mapping services, land surveying, and an accurate time reference with continuous, accurate, 3D position, and velocity information to users worldwide [29]. GPS consists of three segments, namely, control, space, and user. The control segment consists of five earth stations with master control station located at Falcon Air Force Base in Colorado Springs. The space segment is a set of satellites orbiting around the earth. These satellites provide ranging signals and navigation data messages to users. The user segment, or the GPS receiver, performs the navigation, timing, and other related functions for users [11].

Numerous GPS developments are achieved through continuous silicon technology development and embedded system design advancement, and considerable research efforts achieve low power consumption with high-performance receivers [17, 24, 57]. In mobile devices, batteries are considered an important demand in terms of power consumption. High battery drain restricts the use of mobile devices, thereby degrading the functionality of the device [4, 33]. The high power consumption of GPS receiver chips causes overheating issues and limits the continuity of GPS functions in mobile devices [62]. Furthermore, high power consumption results in a system that is either physically large (to accommodate large batteries) or has a short deployment time (due to reduced battery capacity) [50]. The continuous operation of GPS receivers would consume power but shutting these receivers down extensively would degrade the GPS usability.

Localization accuracy can be considered a key factor for enabling innovative applications that utilize a GPS receiver. However, current commercially available GPS devices experience inaccuracy at varying degrees. A standalone GPS device typically experiences positioning error up to tens of meters, which is distant for many safety-critical applications [35]. GPS-based localization frequently lacks consistency in providing the required accuracy and deficiency that many applications cannot tolerate, especially for mission-critical applications [20].

Ideally, the minimum number of GPS receiver tracking channels required for user position calculation is four [3], Won et al., 2000. In real-time receiver operation, a probable amount of time, where the number of tracking channels of the GPS receiver is less than four, exists. The GPS receiver has no position coordinate readings during this time. This condition should be considered during the design and evaluation phases.

Theoretically, increasing the number of required tracking channels (NRTC) for the GPS baseband receiver increases its design complexity and size. Thus, power consumption significantly increases [31, 45, 59, 65]. Furthermore, additional

satellites should be acquired and tracked by the receiver to improve the location accuracy of a position. This condition requires a high NRTC in the receiver [3, 12]. However, the selection of NRTC for the GPS baseband receiver is a difficult and challenging task because the GPS design parameters of each NRTC have multi-attributes for evaluation. For example, power consumption and localization accuracy are proven to be crucial in this setting because they provide an objective complement to the decision and optimization of a critical factor that affects the outcome of the GPS receiver. Furthermore, each decision maker provides different weights for these attributes (GPS design parameters). On one hand, a GPS baseband receiver designer who aims to provide a core for the number of tracking channels might offer additional weights to power consumption or localization accuracy feature than the other features. On the other hand, developers who aim to improve an optimum GPS baseband receiver for solving this problem may target different attributes. Thus, the optimum tracking channel selection of the GPS baseband receiver is a multi-complex attribute problem.

This study presents the optimum tracking channels of the GPS baseband receiver based on the multi-criteria analysis. Nine operation modes of the GPS receiver are evaluated by each GPS design parameter, such as power consumption, localization accuracy, and time with no position available for static and dynamic positioning. Then, a technique for order performance by similarity to ideal solution (TOPSIS) method is utilized to measure and rank the overall performance of the tracking channel selection. The remaining sections of this paper are organized as follows. Section 2 presents the literature review. Moreover, Sect. 3 describes the decision-making methodology for optimizing the tracking channels of the GPS receiver based on the multi-criteria analysis. Section 4 reports the results and discussions. Section 5 draws the conclusion.

2 Literature review

A typical GPS receiver design consists of radio frequency (RF) front-end module, baseband processor, and embedded software [21]. The RF front-end module receives GPS signals from satellites, filters them, shifts GPS signal frequency down to an intermediate frequency (IF), and finally digitizes them as an input to the baseband processor. The baseband processor acquires a lock status from multiple GPS satellite signals through the correlation process. The software controls the operation of the baseband processor and extracts GPS satellite ephemeris data and position calculation [22, 58]. The current literature on optimizing the tracking channels of GPS receiver is limited and scattered. However, several studies have attempted to create a model for reducing power consumption or improving localization accuracy.

The power consumption of digital baseband receiver can be achieved by utilizing several techniques, such as fast synchronization [40], asynchronous design methodology [62], off-load cloud computation [34,37], and trajectory data utilization [21]. GPS deployment time reduction techniques efficiently use energy and handle the deployment time reduction of GPS receivers. Deployment time reduction can be achieved by adaptive GPS sampling method [21], sensor-assisted GPS localization (such as Wi-Fi, accelerometer, and DGPS) [72], and duty cycle optimization [40,50].

Significant research efforts for power-efficient GPS receiver design can be classified into two categories, namely, RF front-end and baseband receiver. A gate-modulated quadrature voltage controlled oscillator technique has been proposed to reduce the power consumption of RF front-end design with power less than 10 mW [9]. A novel time bias determination method [22] is designed for GPS receivers by powering up the RF front-end module for a sufficient time to receive a single GPS satellite signal and a time bias fix. The system enters a low-power mode by turning off the RF front-end module once the first subframe of GPS ephemeris data is downloaded. This study focused on time bias fix only and did not consider satellite positions, which are important in determining the user position [13]. A 5-channel GPS receiver in [36] is designed with 30 mW power consumption by reducing the GPS duty cycle through fast synchronization; the acquisition time is reduced by adding a set of “stationary” reference local codes. Multiple adders are used per tracking channel; thus, the complexity of the design is large. A new GPS tracking channel in [40], namely, the “Synchronizer,” which functions similar to regular GPS tracking channel but with low acquisition time is designed. The search window of the synchronizer is set to ± 3.5 code chips, and the search is conducted in parallel. Thus, the power duty cycle is reduced. The complexity of this design is high because it uses 42 correlators per tracking channel. The GPS receiver design in [62] proposes using on-the-fly signal processing of GPS signal codes instead of using memory to reduce the consumption of memory access power at the system level. Detailed analyses on the source of power consumption are insufficient, although several previous works [22,40] focused on reducing the total power consumption in the baseband receiver using power gating technique.

By contrast, the localization accuracy achieved by GPS has improved considerably in the last few years. The level of GPS localization accuracy is improved on a system-level design by augmenting GPS with corrections and additional sensors [54]. The acceptable level of GPS localization accuracy for stand-alone SPS services ranges from (9 to 17) m as stated in the GPS standards [18,20,30,32]. However, the performance of SPS service may degrade because of several sources of errors. These errors include satellite geometry effects, GPS ephemeris errors, receiver clock errors, ionospheric delay,

tropospheric delay, receiver noise, and multipath effect. The GPS sources of errors reduce the GPS satellite visibility and GPS signal strength; thus, the receiver provides inaccurate position coordinates. The rapid development of the GPS localization accuracy provides a precise determination of satellite orbital parameters by expanding the GPS satellite constellation and improving the global continuous GPS tracking station coverage [55]. Accurate 3D positions are provided using the Marmara Continuous GPS Network stations during a long-term observation. GPS observations are processed in the ITRF 2005 reference frame using a Bernese 5.0 GPS software [19]. Kalman filter [48,49] is used in the software running on a standard 32-bit embedded microprocessor as a CPU for improving GPS accuracy [53]. An algorithm, namely, distributed location estimate algorithm (DLEA), is proposed to improve the accuracy of vehicle positioning. The implementation of DLEA depends on inaccurate GPS pseudo range measurements and obtained inter-vehicle distances without using any reference points for positioning correction [35]. An inertial navigation system is used along with a GPS or a differential GPS to improve accuracy [23,25,28,48]. A tightly coupled integration approach is implemented based on Kalman filter in [17], and this approach shows an improved accuracy level and system robustness. Another approach to improving GPS localization accuracy is presented in [60] is international global navigation satellite systems service ultra-rapid orbits combined with real-time clock estimation. GPS is used for estimating the location, except if satellite signals are lost, in which the location is estimated using motion measurements. However, the improvement models for localization accuracy do not address the power consumption issues of the receiver.

Therefore, the literature review observations show no evidence of an existing effective strategy for balancing the trade-off among conflicted performance parameters and for determining the optimum tracking channels of the GPS baseband receiver in terms of power consumption and localization accuracy. Thus, the adoption of decision-making algorithms that can solve complex situations among conflicted parameters should be investigated.

3 Methodology

3.1 Conceptual framework

An effective strategy for balancing the trade-off among GPS design parameters should be developed. This condition requires a detailed observation for the alternative of NRTC based on a set of GPS design parameters, such as power consumption, localization accuracy, and time with no position available. A proposed conceptual framework based on multi-criteria decision-making/multi-attribute decision-

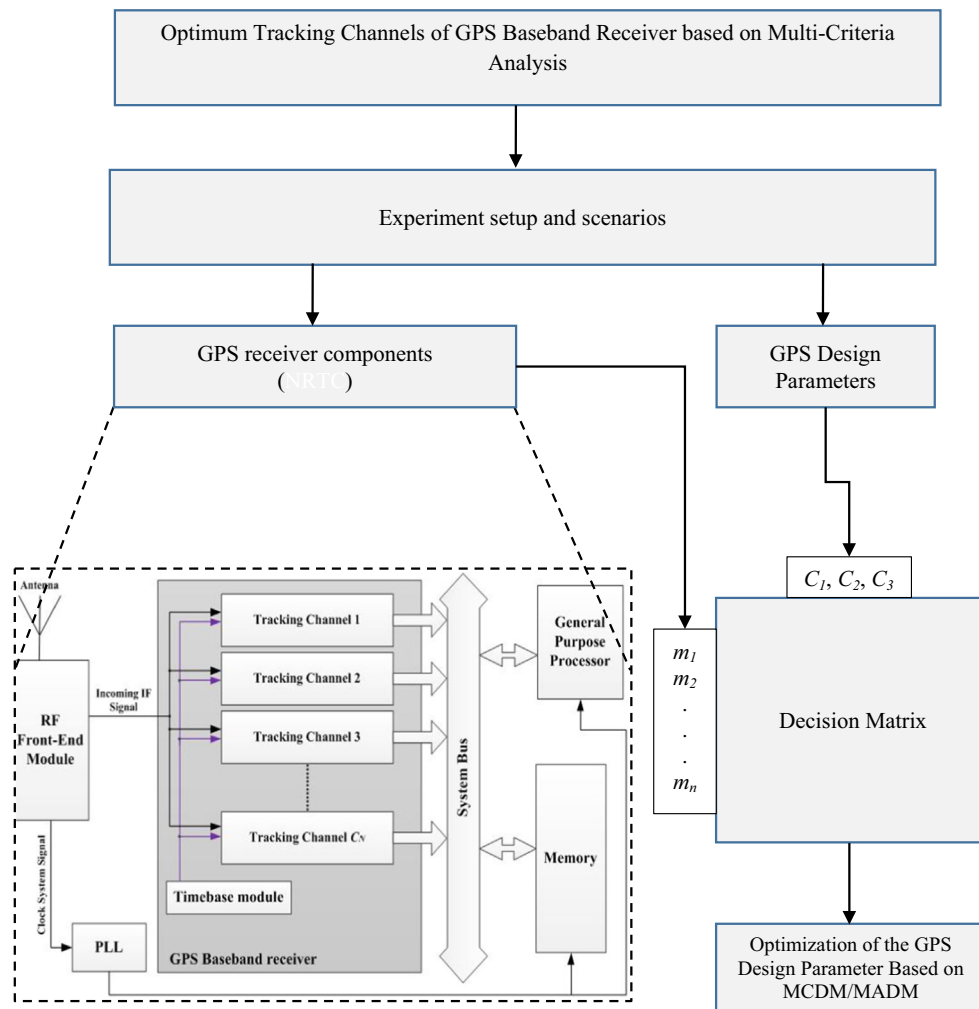


Fig. 1 Conceptual framework

making (MCDM/MADM) techniques was presented for measuring and ranking the overall performance of tracking channel selection. In this study, the conceptual framework consisted of four phases, namely, experiment setup and scenarios, GPS receiver components (NRTC), GPS design parameters, and parameter optimization (MCDM/MADM). The conceptual framework is presented in Fig. 1 and is described in the subsections.

3.2 Experiment setup and scenarios

The implementation of the proposed design was accomplished using a DE0-Nano Cyclone IV FPGA device. Aeroflex configurable GPSG-1000 is a portable, easy-to-use GPS and Galileo positional simulator. It fills the gap in the market by providing a low-cost 12-channel test set that creates 3D simulations (“Aeroflex GPSG-1000 Portable Satellite Simulator,” n.d.). Simulated 3D position may be entered by the user in latitude/longitude/height format or

3D position may be dynamically simulated by utilizing a multi-leg waypoint entry scheme [1]. An unlimited number of navigation plans may be saved and recalled under an assigned user name. Aeroflex simulator contains the simulator system, coaxial cable, and antenna coupler used for transmitting the generated GPS signals by the simulator.

Two scenarios are considered for analyzing the performance of tracking channels:

1. Static positioning with normal environment.
2. Dynamic positioning at 60 km/h speed with normal environment.

Each scenario has five position simulations. The simulated coordinates were selected from the built-in data of Aeroflex GPSG-1000 satellite simulator. The simulation time was set to 1 h per position simulation, and data samples were collected at 1 Hz frequency (3600 data samples per hour). For dynamic positioning in a normal environment, two coordi-

nates were set for each simulation (starting and destination points). The starting points were selected similar to the static positioning scenario coordinates, whereas the destination points were selected randomly. The distance between the starting and destination points was 60 km, and the speed of the simulated vehicle was 60 km/h, which is considered the safe driving speed [7].

3.2.1 GPS receiver components

A typical architecture of hardware-based GPS receiver consists of the following [26]:

1. RF front-end module with antenna (active or passive) for analog signal processing.
2. Phase-locked loop module, which is used for clock system synchronization that utilizes a reference clock signal from the RF front-end module of GPS.
3. Memory unit for storing temporary and permanent data for software computation.
4. General purpose processor running embedded software for controlling components inside the baseband receiver and computing the navigation solution.
5. Baseband processor generally consisting of C_n number of tracking channels and time base module.
6. System bus to link up the internal system components.

In the baseband receiver, the function of a tracking channel is to provide digital signal processing services, such as signal acquisition and tracking. The output data of baseband receiver are transferred to the software, which is running on a general-purpose processor, for computing the user position. The tracking channel typically consists of carrier mixers, code mixers, accumulators, carrier and code numerically controlled oscillators, code generator, and epoch counters. The function of a time base generator is to generate the interrupt and timing signals used in the correlation process of the baseband [26, 39].

During the signal acquisition process, the baseband receiver has C_n tracking channels running for parallel satellite search, as illustrated in Fig. 1. The minimum NRTC for position calculation is four [40]. According to [26], a GPMC algorithm maintains $(4 + m)$ tracking channels with “locked” status and shuts down the rest of the tracking channels, that is, $(C_n - (4 + m))$ tracking channel, where m is the extra tracking channel added to the baseband receiver.

3.2.2 GPS design parameters

The design parameters considered during multi-criteria analysis for m in the GPS baseband receiver are as follows: power consumption, the amount of power consumed during the GPS

receiver operation is a critical issue and has to be addressed [22, 36, 40, 62]. Localization accuracy, an important factor for enabling innovative applications in intelligent transportation systems. T_{no-pos} in real-time receiver operation, a probable amount of time exists where the number of tracking channels of the GPS receiver is less than four. During this time, the GPS receiver has no position coordinate readings. Thus, this parameter is considered a critical parameter that may degrade GPS performance. This parameter is named as T_{no-pos} . Hence, the operation time T of the GPS receiver can be calculated by utilizing the following equation:

$$T = T_{pos} + T_{no-pos}, \quad (1)$$

where T_{pos} represents the time segment when the GPS receiver has position coordinate readings. The procedures for estimating the above quality metrics are described as follows.

1. Power consumption estimation procedure

In this study, the used methodology for power estimation was built according to the methodology used in [62]. The consumed power by 12 tracking channels can be calculated by multiplying the power of one tracking channel in the acquisition and tracking processes by 12.

A Synopsys Design Compiler (Synopsys DC) is used for estimating the power of one tracking channel in each mode [60]. The proposed GPS baseband receiver was synthesized using the Synopsys DC with Silterra 130 nm process technology running at 16 MHz clock frequency. This design requires the minimum frequency of 16 MHz because this parameter is the sampling frequency of the RF front-end module.

A Switching Activity Interchange format (SAIF) file is a widely used power format file that provides information about a switching activity generated by electronic design automation tools (“Synopsys Design Compiler,” n.d.). The use of SAIF file with Synopsys DC showed more accurate power estimation reports than the Synopsys DC power report without SAIF file.

The following procedure should be considered when creating SAIF files: first, the proposed low-power GPS baseband receiver was simulated using ModelSim 10.1d from Altera. The real GPS recorded data obtained from an open-source software-based GPS receiver were designed in MATLAB, and the source code and GPS data samples were printed from a CD with book reference [8]. Three value change dump (VCD) files were generated from the low-power baseband simulation by considering each process in the baseband, which includes signal acquisition, signal tracking, and off-status. Second, VCD files were converted to SAIF files using the vcd2saif tool from Synopsys. Third, the power reports of Synopsys DC utilizing SAIF files were used in

power estimations for the proposed low-power GPS baseband receiver.

2. Localization accuracy estimation procedure

The accuracy of the proposed GPS baseband receiver platform was validated using a cumulative distribution function (CDF) [42,43]. The level of GPS localization accuracy ranged from 9 to 17 m as stated in the GPS standards [18]. Google Earth was used for identifying GPS coordinates, and the results were printed. The ruler tool in Google Earth was utilized for measuring the distances of each circle diameter and road line.

3. T_{no-pos} estimation procedure

T_{no-pos} metric was calculated statistically by counting the number of seconds when the GPS receiver has no position coordinates. Subsequently, the average value of T_{no-pos} for each scenario was used as a GPS design parameter.

During the experiment, the baseband receiver was operating at a range of m (0 – 8) under each scenario. For each value of m , the receiver power consumption, localization accuracy, and T_{no-pos} were estimated. Thus, the selection of m was based on multiple parameters. These parameters are conflicting, and the NRTC selection for the GPS baseband receiver is a MADM/MCDM problem. This problem refers to determining the reference decisions over available alternatives characterized by multiple conflicting attributes. The process of optimizing the best threshold among the conflicting GPS design parameters involves simultaneous consideration of multiple attributes for ranking the available alternatives. Additional details on the fundamental terms of the tracking channel selection of GPS baseband receiver based on multi-criteria analysis are provided in the following section.

3.3 Optimization of the GPS design parameter based on MCDM/MADM

The useful techniques in managing MADM/MCDM problems in the real world are defined as recommended solutions in a collective method to aid decision makers in organizing the problems to be solved and conduct the analysis, comparisons, and ranking of alternatives or multiple platforms [6,46,47]. Accordingly, selecting a suitable alternative is described in the previous literature [44]; the MADM/MCDM methods are suitable for solving the tracking channel selection problem of GPS baseband receiver. The goals of MADM/MCDM are as follows: (1) aid decision makers to select the best alternative, (2) categorize viable alternatives among a set of available alternatives, and (3) rank the alternatives in decreasing order of performance. In particular, MADM problems are encountered under various situations in which a number of decision makers have several alternatives and actions or candidates to select from based on a set of attributes [71]. The MADM

methods are classified based on the type of information provided by decision makers; the three types are no information, information on the attribute, and information on alternative [27]. Thus, the researcher focused on the information on the attribute type. The six popular methods of MADM using different concepts on different domain are multiplicative exponential weighting (MEW), weighted product method (WPM), weighted sum model, simple additive weighting (SAW), hierarchical adaptive weighting, and TOPSIS [67,70]. Various multi-criteria decision-making algorithms create another challenge for researchers in selecting the most appropriate technique [68]. MCDM problems are encountered under various situations where several decision makers have several alternatives and actions or candidates require being selected based on a set of attributes [52,66,69]. Therefore, the appropriate algorithm should be selected

Several articles have developed comparative studies among these techniques and other techniques to determine the best algorithm. When comparing SAW and TOPSIS, TOPSIS is more robust than SAW theoretically. The former considers the alternative in terms of the most desirable result by considering the distance of each result from the most and the least desirable results. This consideration increases the accuracy of the result. Thus, TOPSIS is recognized as a stronger weighting model than MEW and SAW [56] claim that TOPSIS is a major MADM technique compared with AHP because of the aforementioned advantages of the former. The TOPSIS is considered a major decision-making technique.

Other researchers contended that SAW is the preferred weighted model. For example, [10] discuss the evaluation of eight MADM methods. Based on their investigation, SAW performed better than MEW, TOPSIS, and AHP. Furthermore, the superiority of SAW was discussed in the empirical study of SAW, WPM, and TOPSIS. In conclusion, [10] find that a simple evaluation technique is usually superior to other complex techniques. A major disadvantage of SAW is that establishing the weights is subjective. According to [44], TOPSIS is the best in terms of ranking index among the highest-ranked alternative methods but does not imply that TOPSIS is constantly the closest to the ideal solution. However, the authors do not consider the trade-offs involved in obtaining the aggregating function normalization. Therefore, TOPSIS is considered the best among the major MADM techniques due to its advantage over other MADM and group decision-making techniques [10].

Fundamental terms, such as decision (DM) or evaluation matrix (EM), the alternatives, and criteria, should be defined in any MADM ranking. The EM consisting of m alternatives and n criteria should be created. The intersection of each alternative and criterion is given as x_{ij} . Thus, we obtain a matrix $(x_{ij})_{m \times n}$.

$$D = \begin{matrix} & C_1 & C_2 & \dots & C_n \\ A_1 & \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \end{bmatrix} \\ A_2 & \begin{bmatrix} x_{21} & x_{22} & \dots & x_{2n} \end{bmatrix} \\ \vdots & \begin{bmatrix} \vdots & \vdots & \vdots & \vdots \end{bmatrix} \\ A_m & \begin{bmatrix} x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \end{matrix},$$

where A_1, A_2, \dots, A_m are the possible alternatives, from which decision makers have to select (i.e., NRTC); C_1, C_2, \dots, C_n are the criteria where the performance of each alternative is measured (i.e., power consumption, localization accuracy, and T_{no-pos}); x_{ij} is the rating of alternative A_i with respect to criterion C_j ; and W_j is the weight of criterion C_j . Certain processes, such as normalization, maximization indicator, addition of weights, and other processes depending on the method, should be completed when ranking the alternatives. Additional details are provided in the next section.

3.3.1 TOPSIS

TOPSIS is a MADM method. No previous work utilizing a methodology similar to our proposed method for modeling a sports draft is known. TOPSIS selects the best attributes of DM among all alternatives to create an ideal solution. The alternative closest to the ideal solution and simultaneously farthest from the non-ideal solution is selected [27]. TOPSIS creates an index that combines the closeness and remoteness of an alternative to the ideal and non-ideal solutions, respectively, to perform this selection [51]. TOPSIS generally follows six steps.

Step 1: Construct a normalized DM.

This process aims to transform various dimensional to non-dimensional attributes and enables a comparison of the attributes. The matrix $(x_{ij})_{m \times n}$ is then normalized from $(x_{ij})_{m \times n}$ to matrix $R = (r_{ij})_{m \times n}$ using the following normalization method:

$$r_{ij} = x_{ij} / \sqrt{\sum_{i=1}^m x_{ij}^2}. \tag{2}$$

This process results in a new matrix R , where R is expressed as

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix}.$$

Step 2: Construct a weighted normalized DM.

In this process, a set of weights $w = w_1, w_2, w_3, \dots, w_j, \dots, w_n$ from the decision maker is accommodated to the normalized DM. The resulting matrix can be calculated by multiplying each column from the normalized DM

(R) with its associated weight w_j . The set of weights is equal to 1.

$$\sum_{j=1}^m w_j = 1. \tag{3}$$

This process results in a new matrix V , where V is presented as follows:

$$V = \begin{bmatrix} v_{11} & v_{12} & \dots & v_{1n} \\ v_{21} & v_{22} & \dots & v_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ v_{m1} & v_{m2} & \dots & v_{mn} \end{bmatrix} = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \dots & w_n r_{1n} \\ w_1 r_{21} & w_2 r_{22} & \dots & w_n r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ w_1 r_{m1} & w_2 r_{m2} & \dots & w_n r_{mn} \end{bmatrix}.$$

Step 3: Determine the ideal and non-ideal solutions.

In this process, two artificial alternatives, namely, A^* (i.e., ideal alternative) and A^- (i.e., non-ideal alternative), are defined as

$$A^* = \left\{ \left(\left(\max_i v_{ij} \mid j \in J \right), \left(\min_i v_{ij} \mid j \in J^- \right) \mid i = 1, 2, \dots, m \right) \right\} = \{v_1^*, v_2^*, \dots, v_j^*, \dots, v_n^*\}, \tag{4}$$

$$A^- = \left\{ \left(\left(\min_i v_{ij} \mid j \in J \right), \left(\max_i v_{ij} \mid j \in J^- \right) \mid i = 1, 2, \dots, m \right) \right\} = \{v_1^-, v_2^-, \dots, v_j^-, \dots, v_n^-\}, \tag{5}$$

where J is a subset of $\{i = 1, 2, \dots, m\}$, which presents the benefit attribute (i.e., an increasing utility with its high values is provided), whereas J^- is the complement set of J and the opposite could be added for the cost-type attribute, as denoted by J_c .

Step 4: Calculate the separation measurement based on Euclidean distance.

In this process, the separation measurement is completed by calculating the distance between each alternative in V and deal vector A^* by using Euclidean distance, which is expressed by

$$S_{i^*} = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^*)^2}, i = (1, 2, \dots, m). \tag{6}$$

Similarly, the separation measurement for each alternative in V from non-ideal A^- is given by

$$S_{i-} = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}, i = (1, 2, \dots, m). \quad (7)$$

Two values, namely, S_{i^*} and S_{i-} , for each alternative were counted by the end of Step 4. The two values represent the distance between each alternative and the ideal and non-ideal alternatives.

Step 5: Calculate the closeness to the ideal solution.

In this process, the closeness of A_i to ideal solution A^* is defined as follows:

$$C_{i^*} = S_{i-} / (S_{i-} + S_{i^*}), 0 < C_{i^*} < 1, i = (1, 2, \dots, m), \quad (8)$$

where $C_{i^*} = 1$ if and only if ($A_i = A^*$). Similarly, $C_{i^*} = 0$ if and only if ($A_i = A^-$).

Step 6: Rank the alternative according to the closeness to the ideal solution.

The set of alternative A_i can then be ranked in descending order of C_{i^*} . A high value implies an enhanced performance.

4 Discussion results and evaluation

The optimal NRTC are selected based on a set of GPS design parameters, such as power consumption, localization accuracy, and time with no available position for static and dynamic positioning scenarios. The overall success of the optimum number of tracking channels for GPS baseband receiver depends on the balanced performance of conflicting attributes. Accordingly, the discussion results are based on two main sections, namely, DM and TOPSIS-based parameter optimization.

4.1 DM

The power consumption was estimated by using Synopsys DC power reports with SAIF files. The design was synthesized using Synopsys DC with Silterra 130 nm process technology running at 16 MHz clock frequency. These power reports were generated after compiling and synthesizing the GPS baseband design files with SAIF files for determining the input signal activity of GPS raw data from satellites. VCD files were converted to SAIF files using a vcd2saif tool from Synopsys and were used with Synopsys DC for estimating power consumption.

The error of GPS coordinates refers to the distance between the actual (the real coordinates) and reading coordinates from the GPS receiver [63]. Thus, Haversine formula was utilized

to calculate the error of GPS coordinates. Haversine is the name of a trigonometric function that can be used for calculating the distance between two coordinates [14, 15, 41].

The accuracy of GPS receiver was estimated by calculating the median value of CDF for static and dynamic positioning scenarios. The error readings for each simulation scenario were averaged from the positioning areas (Malaysia, Kenya, Saudi Arabia, Ecuador, and Mexico) to calculate CDF. Then, error values for each scenario were ordered ascendingly. For each error value, CDF was calculated by dividing the current simulation time value (in seconds) over the total seconds of simulation scenario. The median value can be illustrated as 0.5 CDF value. Finally, T_{no-pos} was calculated statistically by accumulating the number of seconds in which no GPS position readings exist for static and dynamic positioning scenarios. Table 1 elaborates the GPS receiver design parameters and summarizes the results of each design parameter with different operation modes.

4.2 TOPSIS-based parameter optimization

Nine operation modes of GPS receiver are evaluated by each design parameter, such as power consumption, localization accuracy, and time with no position available for static and dynamic positioning scenarios. However, the task of selecting the optimum number of tracking channels for GPS baseband receiver remains to be achieved. Each m is represented by a set of numbers that represent the performance of m per test. TOPSIS is used for measuring the overall performance of m and ranks them.

In our case study, two scenarios are considered for measuring m . First, multi-criteria analysis with equally treated parameters is used to select the optimum m where the importance of power consumption, localization accuracy, and T_{no-pos} are equal. Second, multi-criteria analysis with conflicting measurements is used to assign different preference weights to power consumption, localization accuracy, and T_{no-pos} . Data tables for both scenarios are presented in "Appendix" Tables 2, 3, 4, 5, 6, 7, 8.

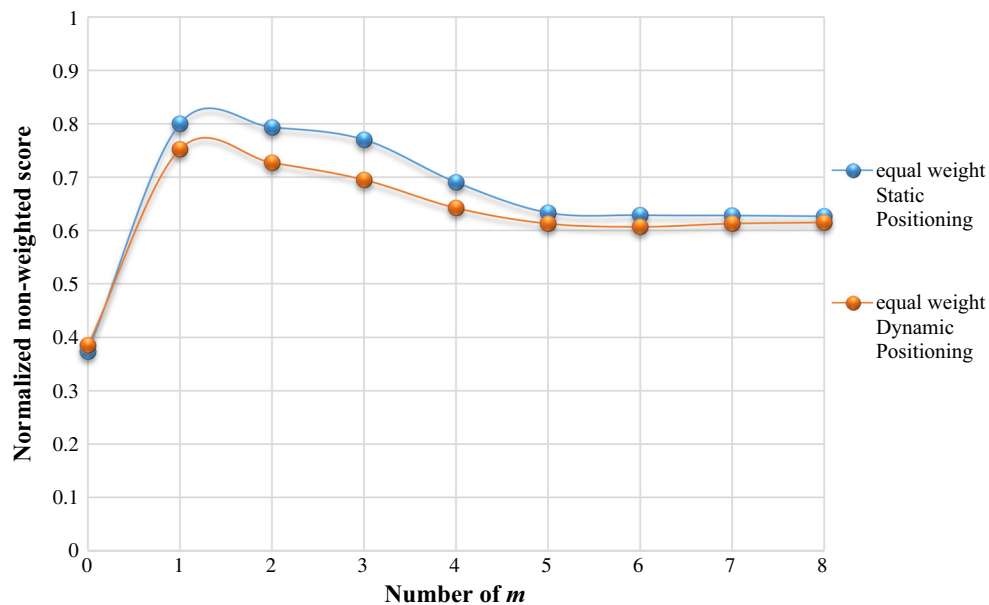
• Multi-criteria analysis with equally treated parameters

The optimum value of m based on the GPS receiver design parameters can be calculated by utilizing the multi-criteria analysis. This analysis was applied to the DM parameters for the static and dynamic positioning scenarios. The level of importance of each parameter was set to an equal value; therefore, the effect of each parameter would be evident on the performance of the receiver. The multi-criteria analysis of non-weighted design metrics is illustrated in Fig. 2.

In Fig. 2, the peak value of the chart represents the optimum GPS receiver performance and can be achieved when $m = 1$ (i.e., five tracking channels). After acquiring 5 satellites ($m = 1$), the accuracy would be significantly improved,

Table 1 GPS receiver DM parameters

GPS receiver operation mode	Static positioning			Dynamic positioning		
	Power (mW)	T_{no-pos} (s)	Accuracy (m)	Power (mW)	T_{no-pos} (s)	Accuracy (m)
$m = 0$	1.986	1623.8	10.3	2.06	1677.2	13.1
$m = 1$	2.255	711.6	9.2	2.356	870	11.34
$m = 2$	2.773	691.8	8.8	2.97	861.2	10.96
$m = 3$	3.296	674.4	8.1	3.502	840.2	10.52
$m = 4$	4.085	655.6	8	4.206	820.4	9.74
$m = 5$	4.765	637.6	7.9	4.909	713.2	9.3
$m = 6$	4.889	629.8	7.6	5.088	690.8	8.98
$m = 7$	4.977	620.4	7.2	5.09	682.4	8.5
$m = 8$	5.06	616.4	6.7	5.092	677.4	8.34

**Fig. 2** Multi-criteria analysis of non-weighted metrics

and T_{no-pos} would be reduced. When acquiring 4 satellites, the probability of losing the position would be increased because losing one satellite lock causes the receiver to lose its position. When $m = 0$, the receiver showed the worst performance because the value of power was slightly decreased with the huge increase in localization accuracy and T_{no-pos} parameters. Furthermore, the receiver showed an approximation of equality in performance when $m > 5$ (i.e., nine tracking channels and above). This behavior was due to the GPS satellite visibility. The standard GPS satellite constellation denotes that 12 satellites are constantly available at any time and place. Moreover, 7–8 satellites can be acquired most frequently in a real environment, and the rest of the satellites are considered visible rare cases. The increase in the number of received satellites would not affect the design metrics. When m is increased from 5 to 8, the system presented higher accuracy and lower T_{no-pos} than $m = 1$. However, a high

level of power consumption would be required to operate 9 to 12 tracking channels.

• Multi-criteria analysis with conflicting measurements

Each metric was compared with the two other metrics to measure the design metric trade-off. Other metrics were assigned with equal weights considering that we aim to measure the effect of one metric. The given weight is decreasing from 1 to 0, with 0.1 amounts. The reduced ratio was divided between the two parameters. Each graph had an intersection point, where all curves passed through, during the trade-off calculations. This point was obtained from the intersection of 100 and 0% parameter importance curves. Furthermore, all other curve weights passed through this point. This test was conducted to provide two measurements per criterion, namely, without conflict trade-off (when $w = 0$ and 1) and with trade-off measurements, to evaluate

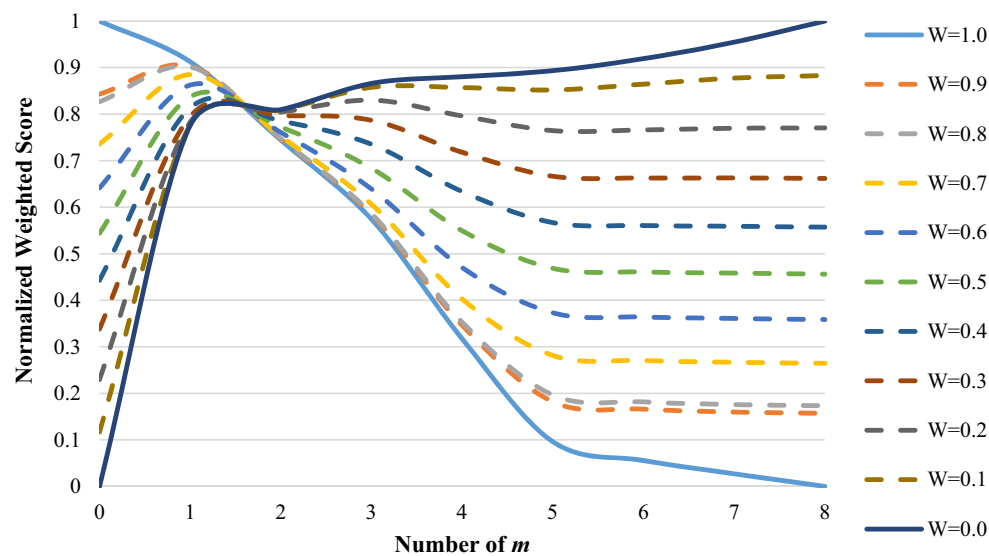


Fig. 3 Power consumption trade-off measurement versus accuracy and T_{no-pos} for static positioning

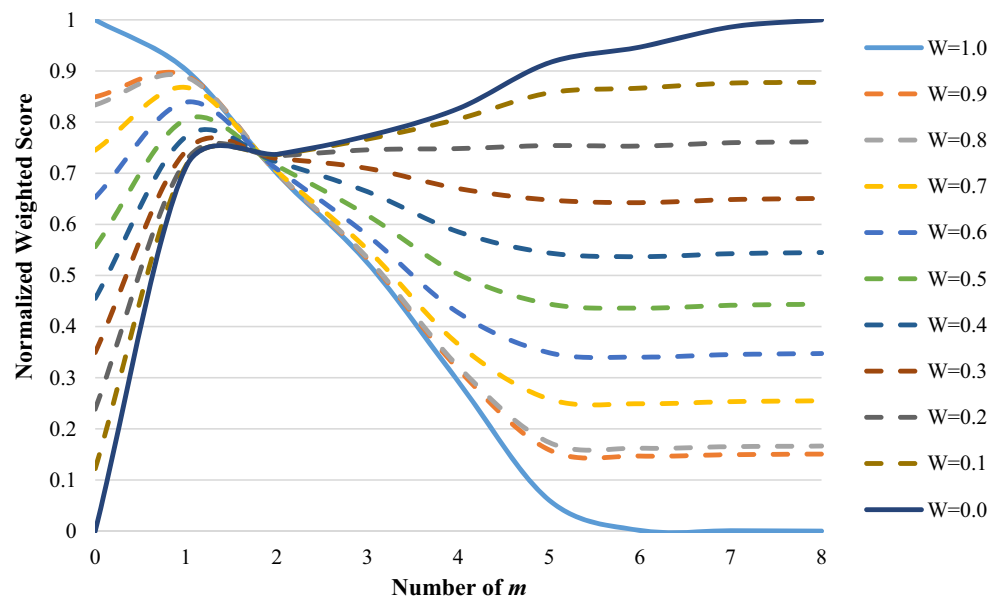


Fig. 4 Power consumption trade-off measurement versus accuracy and T_{no-pos} for dynamic positioning

the conflict between the measured criterion and other criteria.

For the dynamic positioning scenario, the system showed a similar behavior as the static positioning with an increase in m values for the curve intervals. This condition is due to the dynamic nature of the receiver during this scenario, where the probability of losing satellite signals would be increased.

The power consumption trade-off versus localization accuracy and T_{no-pos} are illustrated in Figs. 3 and 4 for static and dynamic positioning scenarios, respectively. In Figs. 3 and 4, the outcome is 100% dependent on power consumption when weight=1.0. Two intervals were observed in the

curve behavior when $m < 5$ and ≥ 5 . For the first curve interval, the curve was degraded from 100 to 10%, whereas the curve was degraded slightly by approximately 10% during the second interval. This condition is due to the operation time was dedicated to the signal acquisition during $m = 5-8$. These results confirm that the available satellites are 8, and the other number of satellites was rarely acquired.

When $w=0$, the power consumption had no effect on system behavior. The $w=0$ curve had three intervals when m is from 0–1, 1–5, and > 5 . During the first interval, the performance of accuracy and T_{no-pos} were increased by approximately 80% by adding one channel. In the second interval, the per-

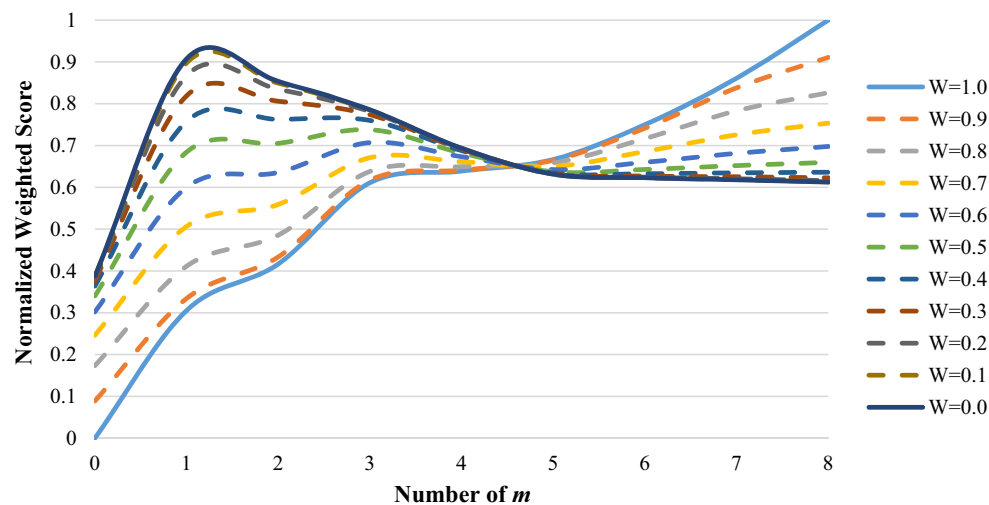


Fig. 5 Localization accuracy trade-off measurement versus power consumption and T_{no-pos} for static positioning

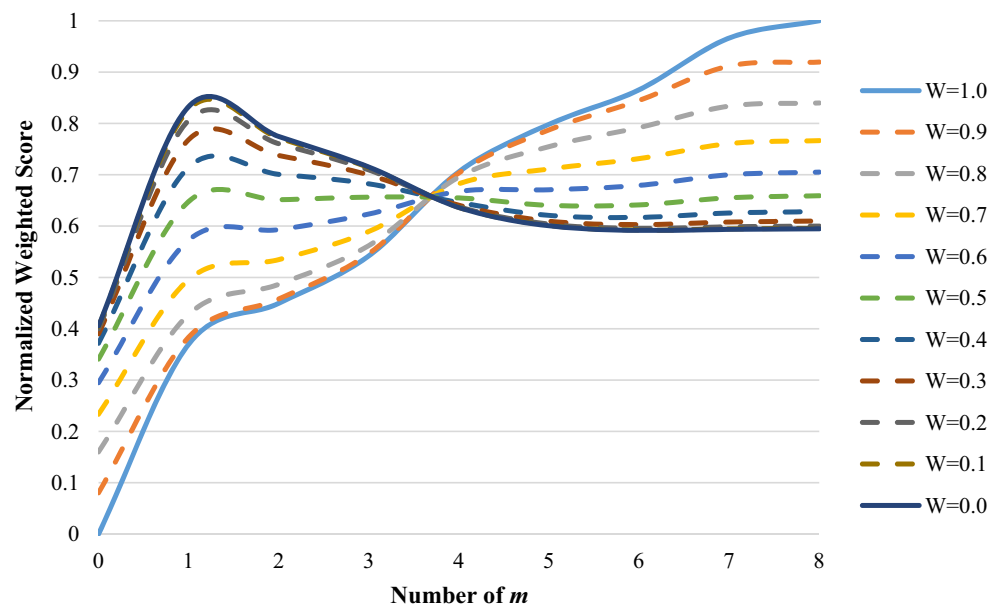


Fig. 6 Localization accuracy trade-off measurement versus power consumption and T_{no-pos} for dynamic positioning

formance of accuracy and T_{no-pos} were increased to 10%. The performance was increased to 10% for the third interval. Furthermore, the system showed equal behavior when $m > 5$ for all of the curves, except $w = 1.0$ and 0 . Thus, the number of m should be reduced when operating the receiver with optimum power saving plan.

The localization accuracy trade-off versus power consumption and T_{no-pos} is depicted in Figs. 5 and 6 for static and dynamic positioning scenarios, correspondingly. In Figs. 5 and 6, the outcome is 100% dependent on localization accuracy when $w = 1.0$. Localization accuracy would increase exponentially while m increases. When $m = 4$, the accuracy performance increased by approximately 65% compared

with $m = 0$. In addition, a 35% performance increase was noticed when $m = 5-8$. When $w = 0$, the performance of accuracy was increased from 40 to 94%. Then, the performance was decreased by approximately 30% when $m = 1-5$. Subsequently, the performance stabilized when $m \geq 5$. A slight increase was observed when $m > 5$ for all the curves, except $w = 1.0$ and 0 . Therefore, increasing m would enhance localization accuracy.

T_{no-pos} trade-off versus power consumption and localization accuracy metrics is displayed in Figs. 7 and 8 for static and dynamic positioning scenarios, respectively. In Figs. 7 and 8, the outcome is 100% dependent on T_{no-pos} when weight = 1.0. When $w = 1$, the performance of T_{no-pos} was

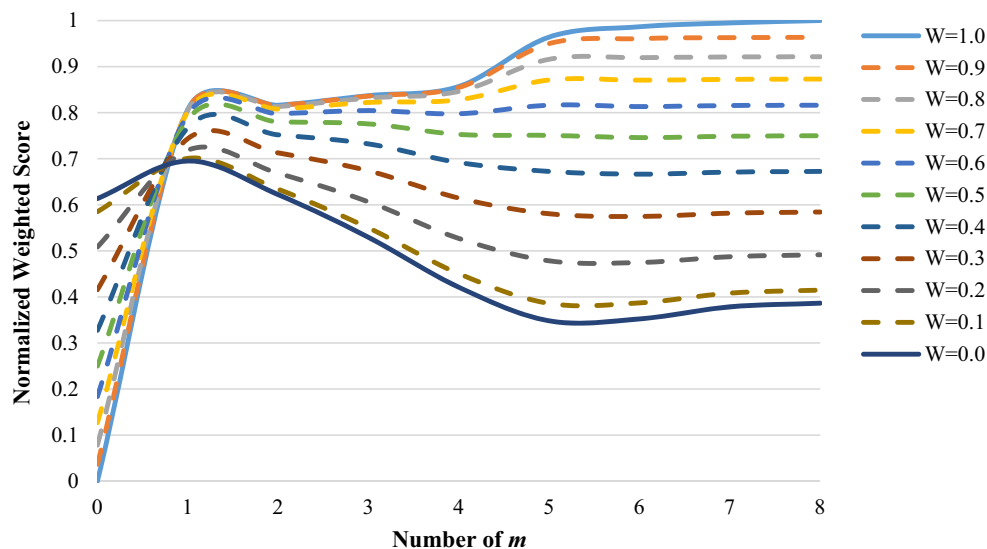


Fig. 7 T_{no-pos} trade-off measurement versus power consumption and accuracy for static positioning

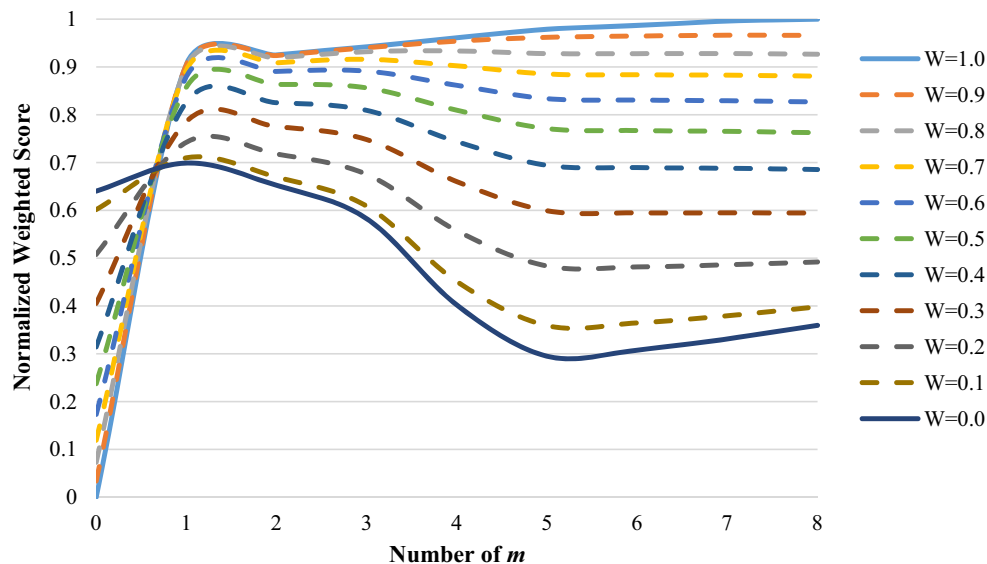


Fig. 8 T_{no-pos} trade-off measurement versus power consumption and accuracy for dynamic positioning

significantly increased by approximately 85% compared with $m = 0$. Then, approximately 5% of the increase in performance can be observed when $m = 1-4$. When $m \geq 5$, the performance was nearly stabilized. The system showed equality while m increases. A slight increase was observed when $m > 5$ for all the curves, except $w=1.0$ and 0. Therefore, increasing m would slightly enhance T_{no-pos} .

4.3 Main claims

In the previous section, we discussed the behavior of each performance parameter of the GPS receiver and the trade-off

among the parameters. The main claims of this study can be summarized as follows:

1. A clear trade-off is observed between power consumption, localization accuracy, and T_{no-pos} when increasing or decreasing m .
2. NRTC should be decreased to develop an optimum power-saving GPS receiver. However, NRTC must be increased to achieve high localization accuracy and low T_{no-pos} .
3. In the trade-off measurement of power consumption versus localization accuracy and T_{no-pos} , two intervals are

found in the behavior with high ($m < 5$) and slight decreases ($m \geq 5$).

4. In the trade-off measurement of localization accuracy versus power consumption and T_{no-pos} , two intervals are found in the behavior with high ($m < 5$) and moderate increases ($m \geq 5$).
5. In the trade-off measurement of T_{no-pos} versus power consumption and localization accuracy, three intervals are found in the behavior with significant ($m \leq 1$) and slight increases ($m = 1-4$) and stable performance ($m > 5$).
6. The multi-criteria analysis is a reliable strategy for visualizing the trade-off between GPS performance metrics and for providing a dynamic power consumption planning.
7. The best aggregated performance for the GPS receiver is achieved when $m = 1$ or 2 for static and dynamic positioning, respectively.
8. In the literature, researchers reported that the available GPS satellites are constantly 12 at any time and place. However, the most frequent number of available satellites based on our experiment is 8, whereas the other number of satellites rarely occurs.
9. Static and dynamic positioning scenarios provide inline performance behavior. However, a shift is observed in the number of channels (m).
10. In the future, a significant increase will be observed in the number of tracking channels of the receiver with the emergence of GNSS. Therefore, the multi-criteria analysis should be adopted to develop the optimum GNSS receiver.

5 Conclusion

An optimum GPS baseband receiver design utilizing multi-criteria analysis was presented. Localization accuracy would be significantly improved with the increase of tracking channels in the GPS baseband receiver. However, power consumption would be extensively increased. Thus, optimizing

NRTC to balance the conflict among the performance parameters is a difficult and challenging task. Nine operation modes of GPS receiver were evaluated by each GPS design parameter, such as power consumption, localization accuracy, and time with no position available for static and dynamic positioning. The TOPSIS method was utilized for measuring and ranking the overall performance of tracking channel selection. Considerable studies assessing the effect of multipath environment on GPS receivers in static and dynamic positioning would be required in the future.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

Appendix

See Tables 2, 3, 4, 5, 6, 7, 8.

Table 2 Multi-criteria analysis with non-weighted metrics

m	Equal weight static positioning	Equal weight dynamic positioning
0	0.373542307	0.385174526
1	0.799960207	0.752039534
2	0.793137891	0.726838086
3	0.770088514	0.694821518
4	0.690161976	0.642005132
5	0.633177474	0.612674641
6	0.628569879	0.606695789
7	0.627849394	0.612683608
8	0.626457693	0.614825474

Table 3 Power consumption trade-off measurement versus accuracy and T_{no-pos} for static positioning

m	W=1.0	W=0.9	W=0.8	W=0.7	W=0.6	W=0.5	W=0.4	W=0.3	W=0.2	W=0.1	W=0.0
0	1.000	0.843	0.827	0.736	0.641	0.544	0.443	0.338	0.230	0.117	0.000
1	0.912	0.903	0.901	0.885	0.863	0.837	0.813	0.794	0.783	0.777	0.775
2	0.744	0.746	0.747	0.752	0.761	0.772	0.785	0.797	0.805	0.809	0.810
3	0.574	0.584	0.586	0.606	0.639	0.684	0.735	0.787	0.830	0.858	0.866
4	0.317	0.346	0.353	0.402	0.470	0.549	0.634	0.718	0.796	0.857	0.880
5	0.096	0.182	0.196	0.281	0.373	0.469	0.567	0.666	0.765	0.852	0.893
6	0.056	0.166	0.181	0.271	0.364	0.461	0.561	0.663	0.766	0.864	0.919
7	0.027	0.160	0.176	0.267	0.361	0.458	0.559	0.663	0.770	0.877	0.955
8	0.000	0.157	0.173	0.264	0.359	0.456	0.557	0.662	0.770	0.883	1.000

Table 4 Power consumption trade-off measurement versus accuracy and T_{no-pos} for dynamic positioning

m	W=1.0	W=0.9	W=0.8	W=0.7	W=0.6	W=0.5	W=0.4	W=0.3	W=0.2	W=0.1	W=0.0
0	1.000	0.849	0.834	0.745	0.653	0.556	0.455	0.349	0.239	0.122	0.000
1	0.902	0.891	0.888	0.868	0.839	0.805	0.772	0.744	0.725	0.715	0.712
2	0.700	0.701	0.701	0.704	0.708	0.715	0.722	0.729	0.734	0.736	0.737
3	0.524	0.532	0.534	0.551	0.579	0.618	0.664	0.709	0.746	0.767	0.773
4	0.292	0.316	0.322	0.365	0.427	0.502	0.585	0.670	0.748	0.806	0.827
5	0.060	0.159	0.173	0.258	0.349	0.444	0.544	0.648	0.754	0.857	0.916
6	0.001	0.147	0.162	0.249	0.340	0.436	0.537	0.643	0.753	0.866	0.947
7	0.001	0.150	0.165	0.253	0.345	0.442	0.543	0.649	0.760	0.876	0.986
8	0.000	0.151	0.166	0.255	0.347	0.444	0.545	0.651	0.761	0.878	1.000

Table 5 Localization accuracy trade-off measurement versus power consumption and T_{no-pos} for static positioning

m	W=1.0	W=0.9	W=0.8	W=0.7	W=0.6	W=0.5	W=0.4	W=0.3	W=0.2	W=0.1	W=0.0
0	0.000	0.089	0.174	0.246	0.302	0.340	0.364	0.377	0.384	0.387	0.388
1	0.306	0.334	0.411	0.507	0.600	0.684	0.758	0.819	0.867	0.898	0.907
2	0.417	0.434	0.486	0.559	0.636	0.705	0.763	0.806	0.835	0.849	0.853
3	0.611	0.617	0.638	0.671	0.707	0.738	0.760	0.774	0.781	0.785	0.786
4	0.639	0.641	0.649	0.661	0.673	0.682	0.688	0.691	0.693	0.693	0.694
5	0.667	0.665	0.658	0.650	0.643	0.637	0.634	0.633	0.632	0.632	0.631
6	0.750	0.742	0.717	0.686	0.660	0.643	0.633	0.627	0.624	0.623	0.623
7	0.861	0.838	0.783	0.726	0.681	0.652	0.635	0.625	0.621	0.619	0.618
8	1.000	0.911	0.826	0.754	0.698	0.660	0.636	0.623	0.616	0.613	0.612

Table 6 Localization accuracy trade-off measurement versus power consumption and T_{no-pos} for dynamic positioning

m	W=1.0	W=0.9	W=0.8	W=0.7	W=0.6	W=0.5	W=0.4	W=0.3	W=0.2	W=0.1	W=0.0
0	0.000	0.080	0.160	0.233	0.295	0.341	0.372	0.390	0.400	0.404	0.405
1	0.370	0.383	0.428	0.496	0.573	0.648	0.714	0.768	0.806	0.827	0.833
2	0.450	0.458	0.487	0.535	0.593	0.651	0.701	0.738	0.760	0.772	0.775
3	0.542	0.546	0.562	0.590	0.624	0.656	0.682	0.700	0.709	0.714	0.715
4	0.706	0.704	0.696	0.682	0.668	0.655	0.646	0.641	0.638	0.636	0.636
5	0.798	0.787	0.755	0.711	0.671	0.640	0.621	0.610	0.604	0.601	0.601
6	0.866	0.845	0.792	0.731	0.679	0.641	0.617	0.603	0.596	0.592	0.592
7	0.966	0.912	0.834	0.761	0.700	0.655	0.625	0.608	0.599	0.595	0.594
8	1.000	0.920	0.840	0.767	0.705	0.659	0.628	0.610	0.600	0.596	0.595

Table 7 T_{no-pos} trade-off measurement versus power consumption and accuracy for static positioning

m	W=1.0	W=0.9	W=0.8	W=0.7	W=0.6	W=0.5	W=0.4	W=0.3	W=0.2	W=0.1	W=0.0
0	0.000	0.034	0.073	0.119	0.173	0.238	0.314	0.405	0.508	0.602	0.640
1	0.905	0.905	0.901	0.894	0.880	0.858	0.826	0.786	0.743	0.710	0.699
2	0.925	0.924	0.919	0.909	0.891	0.864	0.825	0.775	0.718	0.670	0.652
3	0.942	0.940	0.932	0.916	0.891	0.856	0.809	0.748	0.675	0.609	0.583
4	0.961	0.954	0.934	0.902	0.862	0.810	0.744	0.660	0.557	0.451	0.402
5	0.979	0.962	0.928	0.885	0.834	0.771	0.694	0.599	0.484	0.359	0.295
6	0.987	0.965	0.928	0.884	0.831	0.767	0.690	0.595	0.482	0.365	0.308
7	0.996	0.966	0.928	0.883	0.829	0.765	0.688	0.595	0.486	0.380	0.332
8	1.000	0.966	0.927	0.881	0.827	0.762	0.686	0.595	0.492	0.398	0.360

Table 8 T_{no-pos} trade-off measurement versus power consumption and accuracy for dynamic positioning

m	W=1.0	W=0.9	W=0.8	W=0.7	W=0.6	W=0.5	W=0.4	W=0.3	W=0.2	W=0.1	W=0.0
0	0.000	0.036	0.078	0.127	0.184	0.250	0.327	0.416	0.508	0.585	0.614
1	0.807	0.807	0.806	0.802	0.796	0.785	0.767	0.744	0.719	0.701	0.695
2	0.816	0.816	0.813	0.808	0.798	0.780	0.752	0.713	0.668	0.634	0.622
3	0.837	0.836	0.832	0.822	0.805	0.776	0.732	0.674	0.606	0.550	0.529
4	0.857	0.855	0.846	0.828	0.798	0.753	0.692	0.615	0.527	0.450	0.421
5	0.964	0.950	0.916	0.871	0.816	0.751	0.673	0.581	0.478	0.386	0.348
6	0.987	0.961	0.920	0.871	0.813	0.746	0.667	0.575	0.475	0.387	0.352
7	0.995	0.963	0.921	0.872	0.816	0.749	0.671	0.582	0.487	0.408	0.378
8	1.000	0.964	0.922	0.873	0.816	0.750	0.673	0.584	0.492	0.415	0.386

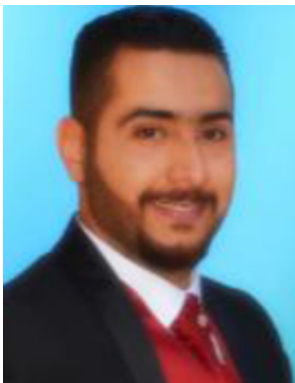
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F. M. Jumaah received his first-class B.Sc. degree in Communications and Electronics Engineering in 2007 from University of Technology, Baghdad, Iraq. Then, he received his M.Sc. degree on Computers and Embedded Systems in 2015 from University Putra Malaysia, Malaysia. After that, he joined ALTERA Corporation as Embedded Systems and Applications Engineer, Global Applications Engineers Malaysia. Currently, he is working with

Intel Corporation as Embedded Systems and Applications Engineer, Global Applications Engineers. His research areas are: Embedded System Design, GPS, Hardware Design, Field Programmable Logic Array, Autonomous Driver Assistance Systems (ADAS), Multiple-Criteria Decision-Making (MCDM).



A. A. Zaidan received his first class B.Eng. degree in Computer Engineering in 2004 from University of Technology, Baghdad, Iraq. Then, he received his M.Sc. degree on Data Communications and computer network in 2009 from University of Malaya, Malaysia. Then, following his Ph.D degree on artificial intelligence in 2013 from Multimedia University, Malaysia. Currently, he is in working as senior lecturer at Department of computing, University Pendidikan Sultan

Idris. He led or member for many funded research projects and He has published more than 130 papers at various international conferences and journals. His research areas are: Information Security (Steganography and Digital Watermarking), Image Processing (Skin Detectors), Pattern Recognition (Classification and Prediction), Machine Learning (Neural Network, Fuzzy Logic and Bayesian) Methods. Multiple-Criteria Decision-Making (MCDM).



B. B. Zaidan received his B.Sc. in Applied Mathematics in 2004 from Al-Nahrain University, Baghdad, Iraq, in 2009. He received his M.Sc. in Data communications and Information Security from University of Malaya, Malaysia. Currently, he is in working as senior lecturer at Department of computing, University Pendidikan Sultan Idris. He led or member for many funded research projects and He has published more than 130 papers at various international

conferences and journals. His research interests include Risk Analysis, Security Policy, AI Applications on Security, Cyber Security, Telemedicine Security, and Security Analysis of e-health, m-health.



R. Bahbib is currently a senior lecturer in the Department of Computing, Sultan Idris Education University, Malaysia. Having received a B.Eng. (Electrical) from Vanderbilt University, USA, a M.Eng.Sc. from Multimedia University, Malaysia and D.Phil. in Eng. Science from University of Oxford, UK, she is keen in applying the technical and research skills gained in improving the quality of education and research in Malaysia. She had been invited to review

articles for high impact journals and conferences. Her research interests include Image and Signal Processing, Ultrasound and other medical imaging modalities, Pattern Recognition, Machine Learning and Fetal/Child Development. She is also the deputy director of the National Child Development Research Center (NCDRC), Malaysia.



M. Y. Qahtan received his B.Sc. degree in Science of computer in 2007 from Diyala University, Diyala, Iraq. Then, he received his M.Sc. degree in Artificial Intelligent and Networking in 2013 from University Tenaga Nasional of Malaya. Currently, he is in progress to complete his Ph.D. at the Faculty of Art, Computing and Creative Industry, University Pendidikan Sultan Idris, Malaysia. His research interests include evaluation and benchmarking of skin detection,

image pressing and Artificial Intelligent applications in image processing and multi criteria decision making (MCDM), and Ad hoc networking.



A. Sali has been a Senior Lecturer at the Department of Computer and Communication Systems, Faculty of Engineering, University Putra Malaysia (UPM) since April 2010. She obtained her Ph.D. in Mobile and Satellite Communications from University of Surrey, UK, in July 2009, her M.Sc. degree in Communications and Network Engineering from UPM in April 2002 and her B.Eng. degree in Electrical Electronics Engineering (Communications) from University of Edinburgh in 1999. She worked as an Assistant Manager with Telekom Malaysia Bhd from 1999 until 2000. She was involved with EU-IST Satellite Network of Excellence (SatNEx) I and II from 2004

until 2009. She is the principle investigator for projects under the funding bodies Malaysian Ministry of Science, Technology and Innovation (MOSTI), Malaysian Ministry of Higher Education (MoHE), Research University Grant Scheme (RUGS) UPM and The Academy of Sciences for the Developing World (TWASCOMSTECH) Joint Grants. She is also a consultant to Malaysian Ministry of Information, Communication and Culture (MICC) and Petronas Bhd on WSN and satellite communication issues respectively. Her research interests are radio resource management, MAC layer protocols, satellite communications, wireless sensor networks, disaster management applications and 3D video transmissions.