GSM passive coherent location system: performance prediction and measurement evaluation

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Abstract: This study describes the processing scheme of the FKIE (Fraunhofer Institute for Communication, Information Processing and Ergonomics) GSM-based passive coherent location (PCL) system, which consists of an antenna and signal processing adapted to the GSM waveform and of target tracking based on multi-hypothesis tracking. To overcome the limitations from a single bistatic transmitter–receiver pair, fusion of the measurements from different geometries is the key component of a GSM PCL system. The authors demonstrate a significant improvement in target position estimation from the tracking process on the basis of real data and theoretical performance bounds. The impact of the transmitter–target–receiver geometry is discussed and the effect of the exploitation of prior context knowledge (e.g. clutter and land maps) on maritime traffic surveillance is shown.

1 Introduction

Bistatic and passive radar systems enjoy various advantages, which have been mentioned by several authors ([1–3]). At Fraunhofer FKIE (Fraunhofer Institute for Communication, Information Processing and Ergonomics) an experimental GSM passive coherent location (PCL) system has been developed that can use multiple GSM base transceiver stations (BTS) as illuminators [4]. The specific features of this system are: maximum angular discrimination by using a linear array, simultaneous reception of multiple BTS and fusion of multiple bistatic systems to improve accuracy and resolution. In this paper, we demonstrate for the case of maritime surveillance that, despite of the modest range resolution of GSM-based PCL systems, the fusion of multiple illuminators allows good tracking results (in terms of position estimation and track continuity) even in regions with dense traffic scenarios. Our primary objective is to demonstrate improvement of a system with the full processing chain from the antenna down to the fused track outputs. Further improvements by sophisticated signal processing and optimised parameter selection are possible, but not considered here.

Various bistatic combinations have been tested during trials in the Baltic sea region, where many GSM BTS are available. An automatic identification system (AIS) receiver has been used to obtain reference positions and velocities of the vessels in the observed area. This information has been compared with the measurements collected by the PCL system (GSM plots) for validation. Then, the AIS tracks have been compared with the experimental results (GSM tracks) and finally the vessel position estimation error has been calculated. The use of the AIS signals for ground truth verification was considered sufficient for these system verification experiments. Future system performance experiments will require additional sensors, in particular with respect to the detectability of small targets.

Specifically, two aspects are addressed in this paper. The first one concerns the evaluation of the achievable position estimation accuracies and the impact of the bistatic geometry on the system performance. By theoretical analysis, we demonstrate the parametric dependence of the position estimate. In particular, a strong dependence on the adopted geometry is demonstrated. Thus, the optimal selection of BTS and illuminator sectors represents a key factor for future improvements. The theoretical performance bounds are calculated according to predicted probability of detection [5] and Cramér Rao Bound (CRB) [6]. The second aspect is the analysis of the experimental tracking results in this paper, hence, a qualitative comparison can be established. As generally known PCL systems are blind in the transmitter direction (because of the strong direct signal) [7]. Strong clutter appears in these regions, which leads to false detections. Thus the tracking performance decreases considerably, because the extraction or maintenance of tracks belonging to targets with angle-of-arrivals (AOA) in the vicinity of the transmitter is degraded. Moreover, for one of the considered scenarios, a wind park is located near the receiver (within the area of surveillance). This causes additional strong clutter with significant Doppler contribution. To overcome this deficiency, a clutter map is proposed for each bistatic configuration to be exploited by the tracker. The advantages brought by the inclusion of prior information into the processing chain are demonstrated by the experimental results and discussed in this paper.

2 Scenario description

Two trial scenarios were acquired in the Baltic sea. The first one considers the maritime traffic in the Bay of
Mecklenburg. Fig. 1a shows the scenario configuration with the receiver (indicated by circle). As illuminators, seven BTSs (black triangles) in six different locations with specific look directions were selected (two BTS’s were sharing one mast).

The receiver was mounted on a tower of 56 m height shown in Fig. 1c located at the eastern cape of the Fehmarn island [4]. Its field of view (FoV) is represented with the shaded sector (120° FoV and 40 km range [4]). The illumination sectors of the individual BTSs are indicated by small sectors. Each BTS typically covers a 120° sector. Moreover, the white arrow within the receiver FOV shows a typical vessel trajectory following one of the sea lanes in this area. We will concentrate on vessels moving along this trajectory to analyse and discuss the obtained results in the following sections.

The second scenario features the frequent ferry traffic between the Fehmarn island and Rodby in Denmark. At the same time, in the orthogonal direction, dense shipping traffic through the Fehmarn Belt is crossing the ferry lane. For both scenarios, the receiver was mounted at the same position as in the first scenario (Fig. 1a) but with a look direction changed to cover the area of interest. In fact, several potential BTSs exist in this region, nevertheless they all could not be considered simultaneously. This is because of the limited receiver bandwidth (30 MHz) and the widespread carrier frequencies of the potential BTSs. Here, we present the results with a configuration restricted to the three transmitters (Fig. 1b). This is clearly not an optimal configuration, but shows exemplary the good results that can be obtained.

3 Receiver and data processing

The guideline for the system concept was to realise a software defined radar as much as possible. This leads to the design of a uniform linear array (ULA) with 16 elements and 16 digital receivers. The ULA guarantees maximum spatial target discrimination as well as deep and narrow nulling of interference for a given number of channels, hence, minimising the clutter in the transmitter direction [8]. The
output of this array can be used for all tasks: reference signal acquisition, surveillance signal extraction and BTS monitoring.

In the trials, the FKIE receiving system GAMMA-2 shown in Fig. 1d has been used. Each element of the ULA is composed of columns of three Vivaldi antennas (frequency range: 1.5–2.15 GHz), which are summed in the analogue domain. Each column has a 3 dB elevation BW of 27° and a gain of 10 dB (at 1.8 GHz) resulting in an array gain equal to 22 dB. For reception of GSM1800 signals, the distance between the elements is chosen equal to 8 cm. As a compromise between processing speed and flexibility, the digital receiver hardware has been designed to extract in parallel up to eight GSM frequency channels (demodulated I and Q) of 200 kHz width within the system receiving bandwidth of 30 MHz. Each frequency channel is subsequently digitally down converted and stored for further signal processing steps.

As we are interested in a first full system demonstration, we have considered standard signal processing: the reference signal is extracted by conventional beamforming [9]. The FoV for the surveillance signal (−60° to 60°) is sampled by a set of fixed beams in azimuth. For each beam with a given AOA, digital adaptive beamforming and clutter cancellation are performed to obtain the corresponding surveillance signal [8]. The clutter cancellation method used here is based on the projection of the received signal onto the subspace orthogonal to the clutter subspace [10]. The signal power is accumulated by coherent integration. The coherent integration time (CIT) is selected as the longest time in which the target with its dynamic remains in the resolution cell. According to [5] and the given scenario, one obtains a CIT equal to 1.8 s producing a very fine Doppler resolution (0.56 Hz) corresponding to a radial velocity <0.05 m/s. The Doppler is therefore an excellent criterion to distinguish closely located vessels in areas with high target density. Finally, the range-Doppler-bin that exceeds a predefined threshold is declared as detection and is forwarded to the tracker.

The range resolution of a GSM-based PCL system is poor because of the low effective signal bandwidth (81 kHz leading to $\Delta_{\text{range}}=1.9$ km in monostatic case [9]) and in general does not satisfy user requirements. However, the achievable accuracy in range $\sigma_{\text{range}}$ (standard deviation of the peak of the complex ambiguity function) can be significantly better depending on the estimation method used [11]. For a performance prediction, we assume perfect conditions [high signal-to-noise ratio (SNR), perfect system calibration, multipath free reception etc.] and reduce the accuracy investigation to the study of sampling effects.

3.1 Parameter accuracies

To characterise the basic system performance, we assume for parameter estimation a simple bin processing strategy and derive the corresponding accuracies which are independent of the scenario. Of course, a detailed analysis of the achievable accuracies must include all effects, starting with the implemented estimation and calibration algorithms, the environmental effects like multipath and the target SNR. This will be a topic of future research.

We start by considering a simple grid search over the range domain. The grid cell dimension $\Delta_{\text{cell}}$ is selected according to the sampling frequency of the analogue-to-digital converter and is smaller than the resolution limit $\Delta_{\text{range}}$. Thus, the range accuracy for high SNR values is determined by

$$\sigma_{\text{range}}^2 = \frac{\Delta_{\text{cell}}^2}{12}$$

This is based on the assumptions that (i) the unknown target position is uniformly distributed within the cell and (ii) no fine estimation technique is implemented (e.g. interpolation or range monopulse).

In the experiment, the signals are sampled at a frequency equal to 240 kHz. Thus, the monostatic range accuracy is about 360 m. This is less than the range resolution but still not satisfying for a good position estimation of moving targets. It has to be stressed that, when operating in bistatic geometry, the achieved position estimation accuracy depends not only on the measurement errors, but also on the bistatic geometry. Thus, the position estimate can be worse than 360 m.

For the angle estimation, we consider a simple search of the maximum response over the 16 look directions (beams) within the FOV. Thus, again the angular cell $\Delta_{\text{angle}}$ defines the angular accuracy. In the case of a uniformly distributed target over the angular cell and considering an angle bin of $\Delta_{\text{angle}}=7.5^\circ$, the angular accuracy $\sigma_{\text{angle}}$ is about 2.15°. Admittedly, such an angular accuracy can only be attained if targets are well separated without any clutter influence. In reality, clutter cancellation and especially direct signal cancellation is imperfect and this will influence the angular accuracy. To deal with this, we assume that the angle error is distributed over two adjacent beams. Thus, the angular accuracy is $\sim5^\circ$.

Following the same argumentation as above, the Doppler accuracy $\sigma_{\text{Doppler}}$ for an integration time equal to 1.8 s results into 0.56 Hz. This high accuracy compensates the low accuracy in range and allows target discrimination and tracking as will be seen in the sequel.

3.2 Tracking

We follow the sequential processing scheme of track prediction and measurement update. This process is triggered by the incoming measurements at time $t_k$ (time scan $k$).

The prediction step utilises the target propagation model. Here, we use the simple model of nearly constant velocity (e.g. [12]). The posterior density of the target state $x_{k+1}$ at time $t_{k+1}$ given the target state at time $t_k$ is modelled by

$$p(x_{k+1}|x_k) = \mathcal{N}(x_{k+1}; Fx_k, Q)$$

where $F$ is the prediction matrix and $Q$ is the process noise matrix. $\mathcal{N}(a; b, Q)$ denotes a Gaussian density with expectation $b$ and covariance $Q$.

The measurement update is driven by the evaluation of the likelihood function, which needs to be defined according to the passive radar data (see Section 3). The functional relationship between the measurement $z_{i}^{(0)}$ of time $t_i$ from the $i$th Tx–Rx pair (consisting of the bistatic range, Doppler and azimuth) and the target state $x_k$ is given by the non-linear function $h^{(i)}$. By assuming Gaussian measurement noise, the likelihood function is expressed by

$$p\left(z_{i}^{(0)}|x_k\right) = \mathcal{N}\left(z_{i}^{(0)}; h^{(i)}(x_{k+1}), R\right)$$

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with fixed measurement covariance matrix \( \mathbf{R} = \text{diag}(\sigma^2_{\text{range}}, \sigma^2_{\text{angle}}, \sigma^2_{\text{Doppler}}) \), see Section 3.1. On using the described tracking model, the state estimation process can be completed by the propagation of the probability density function. Starting with an initial target state estimate (obtained from transformation of a single bistatic measurement into Cartesian coordinates), the target state estimate at time \( t_k \), described by \( \mathbf{x}_{k|i} \) and covariance matrix \( \mathbf{P}_{k|i} \), is updated according to the measurements at time \( t_{k+1} \) by evaluation of the product

\[
\prod_{i=1}^{N} p(z^{(i)}_{k+1} | x_{k+1}^{(i)}) p(x_{k+1}^{(i)} | x_{k}^{(i)}, \mathbf{x}_{k|i}, \mathbf{P}_{k|i})
\]

where \( N \) is the number of available Tx–Rx pairs. These formulas lead to the well-known Kalman filter equations for track prediction and measurement update. Since for passive radar the measurement equation is non-linear, we use the approximation given by the unscented Kalman filter [14].

Using this centralised tracking approach, the multi-hypothesis tracking (MHT) algorithm [15], which needs to handle the association of measurements with the track-to-track fusion or measurement fusion before tracking is not necessary.

Besides the task of state estimation, the tracking algorithm needs to handle the association of measurements with the targets. This issue is especially important for passive radar applications because of high number of false alarms (see Section 5). Our association strategy is therefore based on the multi-hypothesis tracking (MHT) algorithm [15], which we have applied to passive radar tracking using digital radio and television illumination in [16]. Here, the association between measurements and transmitters was a major task. For the GSM PCL systems, the transmitter association is known and only the association of measurements with the existing target tracks has to be achieved, thus a simplified version of the algorithm is used leading to a one-stage MHT in the Cartesian coordinates. Track extraction is performed directly in Cartesian coordinates following the sequential track extraction procedure described in [17].

According to [15], a predicted hypothesis \( H_{k|i}^{(j)} \) at time \( t_k \) is given by a triple consisting of a state estimate \( \mathbf{x}_{k|i}^{(j)} \), covariance matrix \( \mathbf{P}_{k|i}^{(j)} \) and the corresponding weight \( w_{k|i}^{(j)} \). In the case of a detection by measurement \( z_k^{(i)} \), the updated hypothesis weight is calculated by

\[
w_{k+1|i}^{(j)} = w_{k|i}^{(j)} \cdot \frac{P_D}{P_f} \cdot N(c_k^{(j)}; h(\hat{X}_{k|i}^{(j)}), S)
\]

where \( P_D \) is the probability of detection, \( P_f \) is the false alarm density and \( S \) is the innovation matrix delivered by the Kalman filter update. By adaptive modelling of the \( P_D \) [16] and \( P_f \) prior information can be incorporated in the MHT. In Section 5, we discuss the incorporation of prior knowledge in the form of a clutter map.

4 Performance analysis of multiple GSM BTS configurations

4.1 Theoretical performance bounds

The CRB provides a lower bound to estimation performance [18]. Especially, such performance bounds are useful for analysing different transmitter–receiver geometries. Under the assumptions in Section 3.2, the CRB of the \( i \)th Tx/Rx pair for a single time scan is calculated by the inverse of the Fisher information matrix (FIM)

\[
\text{FIM}(x_i) = \frac{\partial h(x_i)}{\partial x_i} \mathbf{R}^{-1} \frac{\partial h(x_i)}{\partial x_i}
\]

see [19]. The result for fusion of multiple bistatic geometries is simply obtained from the sum of the FIM, that is

\[
\text{FIM}(x_i) = \sum_{i=1}^{N} \text{FIM}(x_i)
\]

The additivity is a property of the information matrix, see [18], and does not depend on the fusion scheme, which is chosen for tracking. In particular, this reflects the theoretical consideration that adding measurements of an additional Tx–Rx pair will result in increase of information and consequently in decrease of the estimation uncertainty (described by the CRB). In reality, we need robust association strategies to avoid degradation of the tracking result, when adding measurements from a poor Tx–Rx configuration. This can be further extended to multiple time scans by incorporation of a target propagation model, see [20]. In particular, when considering multiple time scans, we can analyse the impact of the target velocity estimate (which is based on Doppler measurements) on the position estimate. A performance prediction tool based on CRB calculation for passive radar applications has been developed in [21]. This tool is applied here for the two scenarios.

In a first step, coverage maps for the probability of detection are generated for each bistatic transmitter–receiver pair. These \( P_D^{(i)}(x) \) values are obtained from the radar equation for Swerling I targets for hypothetical target positions on a grid in geographic coordinates [22]. Moreover, the radar horizon is incorporated according to the Tx, Rx and target height and for the modified 4/3 earth radius [23].

Figs. 2a and 3a show the sum of the \( P_D^{(i)}(x) \) values for the scenarios described in Section 2. The maximal value of the colourmap is therefore equal to the number of considered transmitters (i.e. seven in Fig. 2a and three in Fig. 3a). The objective of this representation is to highlight the regions of high and low coverage in terms of detection by multiple transmitters contrary to the cumulative \( P_D \). This is not a characterisation of the \( P_D \) of the fused tracks, but gives the expected number of observations from different bistatic pairs. This has a significant influence on estimation performance as we discuss in the following.

The \( P_D^{(i)} \) for a single Tx–Rx pair is an input parameter for the calculation of the CRB. By use of the information reduction factor as introduced by [24], this results in a scaling of FIM according to \( P_D \cdot \text{FIM} \).

In Fig. 2b and c, the CRB for the expected position and velocity errors is displayed for scenario 1 (Bay of Mecklenburg) for a single time scan. The regions of low coverage as seen in Fig. 2a are excluded from this examination. The calculation is done under the assumption of constant velocity, whereby the velocity in every grid point is simulated with the same speed of 10 m/s and heading vector, which is displayed by an arrow in the lower left corner. In this scenario, the velocity vector was chosen to represent a vessel, as recorded by the AIS data. Fig. 2d displays the CRB evaluated over three time scans.
The estimation performance depends strongly on the number of transmitters that provide detection of the target. However, the bistatic geometry may have an even stronger impact on the estimation result. Here, five transmitters are located nearby, not providing any significant spatial diversity. Thus, no additional gain in the fusion context is seen. On the other hand, the availability of measurements from a dislocated transmitter (left part of the observation area) result in a significant accuracy improvement. Moreover, we note increased errors at the line between receiver and transmitters, which is specifically apparent for the region between the receiver and the five co-located transmitters. When exploiting measurements from different time scans a significant improvement can be observed, which can be alluded to the impact of the motion model and the exploitation of the precise Doppler measurement. Precise velocity estimation further demonstrates the beneficial effect of the high Doppler resolution.

The CRB for the second scenario (Fehmarn Belt) is displayed in Fig. 3. The three transmitters are nearly placed on a line. For a single time scan (Fig. 3b), we obtain large error values in position, especially for the region of the ferry traffic between the Fehmarn island and Rodby in Denmark. Errors are reduced by considering three time scans as shown in Fig. 3c. To show the dependency on the assumed velocity vector (according to the Doppler measurements), the same calculation is done for an alternative velocity vector in Fig. 3d (describing the shipping traffic through Fehmarn Belt), which leads to slightly different results.

4.2 Performance analysis on real data

For validation purposes, AIS information of existing vessels is transformed into the range-Doppler-azimuth domain and compared with the GSM measurements.
associated with this ground truth are selected by the global nearest neighbour technique [12]. The availability of the AIS ground truth can be used for theoretical evaluation and validation of experimental system performance. Specifically, we analyse two exemplary vessels. In scenario 1, a ship moving through the Bay of Mecklenburg is considered. In scenario 2, we consider a ferry which is approaching Fehmarn island from Rodby in Denmark. Trajectories of the two vessels are displayed in Figs. 2a and 3a.

The measurements that have been associated with the ground truth (see Section 4.2) are processed by the UKF to obtain estimates of the target position and velocity as well as the covariances ([16]). The results are displayed in Fig. 4. Please note, that for data evaluation, we use a simplified association strategy based on the AIS data tracking results for the full MHT (without the AIS support) are discussed in Sections 5 and 6.2. Specifically, Figs. 4a and b show sequences of the estimation results. The AIS reference data of the vessel are depicted as grey crosses. The GSM track (for several time scans) is represented by a black cross (mean value of estimated position) and an appended black line (mean velocity), whereas the black ellipses show the corresponding track position uncertainty (described by the track covariance). Finally, the bold ellipses illustrate the position uncertainty given by the plots (after transformation into Cartesian domain) of one time instant for each of the bistatic configurations that provide detection. Uncertainty ellipses are plotted according to $3 \times \text{std}$. In Figs. 4c and d the root-mean-squared position error is plotted over track time.

The Bay of Mecklenburg scenario confirms the importance of the bistatic geometry, which was already noted in Section 4.1. At the given time scan, six of seven BTS provide detection of the target (Fig. 4a). Five of them are from closely spaced transmitters, whereas one has a quasi-orthogonal geometry. The dramatic multi-sensor fusion gain can be seen clearly in this example (black ellipses). Fusion over time (assuming the motion model mentioned above) finally improves the accuracy down to 200 m (Fig. 4c). Specifically, the exploitation of the BTS with the error covariance orthogonal to the other configurations enhances the localisation capability. At the end of the
scenario, the error increases, which is consistent with our expectation from the CRB analysis. At the beginning of the scenario, the error values are higher than expected, which can be traced back to missed detections from some transmitters.

For the Fehmarn Belt scenario, the fusion of the three BTSs delivers indeed a more accurate position estimation than with only one BTS, but it is not satisfying (Fig. 4b). This performance can be referred to the inconvenient choice of the BTSs which are in this example almost on the same line with the trajectory of the ferry. Thus, the corresponding position ellipses coincide. No significant accuracy improvement can be expected from the fusion of the BTSs during the first half of the scenario. Only the fusion over time (according to the adopted motion model) improves the performance. In the second half of the scenario, the target is moving in an area of better estimation performance, which is confirmed by the tracking result (Fig. 4).

These examples emphasise the importance of the transmitter–receiver geometry. Orthogonal bistatic configurations deliver higher fusion gain. Hence, the optimisation of a GSM PCL system as considered in [5] is a key factor for the overall performance. This software for computer-aided system configuration is further developed at FKIE.

5 Clutter reduction

The quality of target tracking is limited by the number of false alarms. In particular, the increased occurrence of false alarms in a specific region will lead to unwanted false tracks. One should note that because of our conventional signal processing and hardware imperfections, we have many false alarms because of clutter residues in BTS direction for each bistatic pair. This applies in particular to the scenario of the Bay of Mecklenburg.

In the second scenario of the Fehmarn Belt, a wind park on the coast of Fehmarn island (see Fig. 1b) caused major problems. Without any treatment the tracking results are dominated by a large number of false tracks, as seen in Fig. 5a. Table 1 explains the visualisation symbols of the tracking results in Figs. 5, 7 and 8.

To improve the tracker performance, procedures have been proposed to generate adaptively a clutter map based on all the collected measurements of the same geographical region ([25, 26]). The clutter map identifies regions of high false alarm level. This means that for each BTS and for each range Doppler cell, a probability value describing the appearance of a false alarm is assigned. The generated clutter map for one BTS is displayed in Fig. 5c. The target returns associated to AIS data have been removed from the adaptive statistic. The contribution of the wind park becomes apparent in the first two range cells. This context information is then exploited by the tracker in the plot to track association by the factor \( p_F \) (influencing the hypothesis weights as discussed in Section 3.2). In addition, we introduce a threshold on the false alarm probability to avoid track initiation in a region of high false alarm level. However, an existing track can be maintained in a clutter region.

In addition to the clutter map, the geographical information of the coastline can be inserted in order to
discard the detections on land. A geographic map of admissible areas, Fig. 5d, is taken into account for the MHT. The exploitation of this information makes the target state estimation more accurate with respect to the target position components, because the effect of a low sensor angular accuracy is limited. It is well known that tracking algorithms are prone to strange behaviours (fluctuations, divergence etc.) in case of low accuracy measurements. The use of context information has been already demonstrated as an effective mean for performance improvement in other maritime applications ([27, 28]). In our system, the map is preloaded before the processing starts. The tracker listens to this context information in two different steps of the processing:

1. when new sensor measurements are received as input for the algorithm and
2. when already existing tracks are predicted.

**Table 1** Visualisation scheme: tracking results

<table>
<thead>
<tr>
<th>tracks</th>
<th>small ship symbols</th>
<th>light grey: high-probability track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>dark grey: low-probability track</td>
</tr>
<tr>
<td></td>
<td></td>
<td>transparent: identify an inactive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>track.</td>
</tr>
<tr>
<td>ground truth (from AIS)</td>
<td>triangles</td>
<td>grey: AIS target detected by the GSM system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>white: no associated measurement</td>
</tr>
<tr>
<td>look direction of receiver and transmitters</td>
<td>shaded area</td>
<td>Wind Park Clutter</td>
</tr>
</tbody>
</table>

Fig. 5  **Clutter reduction**

a GSM tracking results are mainly influenced by the high false alarm level, see also Table 1

b By use of clutter and land maps a clean observation picture can be obtained, see also Table 1

c Clutter map for one BTS

d Geographic information map of coastline

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Fig. 6  Results of signal processing

a ARDM for the ground truth
b Doppler-time-matrix for BTS1
c Doppler-time-matrix for BTS2
In both the cases, the unrealistic cases (e.g. measurements over land, or tracks crossing land) are discarded in order to reduce the number of the hypotheses. By using both forms of the context knowledge (clutter and land map), an impressively clean situation picture can be achieved only on the basis of the GSM measurements (Fig. 5b).

6 Experimental results

The main objective of this section is the comparison of the tracking results with the ground truth provided by the AIS receiver. We also report the results at the signal processing level (before tracking and data fusion) for a better understanding and interpretation of the final results.

6.1 Signal processing results

At the signal processing stage, each bistatic configuration (Tx-Rx-combination) is treated independently. The presentation of experimental results of all possible combinations is beyond the length of this paper. We show results with two selected transmitters covering complementary regions in the Bay of Mecklenburg. One BTS illuminates the upper part of the receiver FOV whereas the second one is oriented to cover the lower sub-sector (see Fig. 1a). These two BTSs are mounted on the same mast covering a 210° wide area and consequently have almost the same behaviour in terms of target range and Doppler shift (with a negligible Doppler difference related to the carrier distance).

During the trial of ∼2 h duration, the measurements were updated every minute. Fig. 6a shows the theoretical
accumulated range-Doppler-matrix over a time of three selected targets calculated from the AIS ground truth. These vessels (G1, G2 and G3 in Fig. 7) started from the south-west edge of the receiver FOV and crossed the illumination sectors of the two BTSs mentioned before. Shortly before the end of the trial (the vessels reached the FOV north-east edge), the AIS traces of G1 (triangles in Fig. 6a) disappeared for an unknown reason. The detection of this vessel could be maintained by the GSM passive radar as can be seen in Figs. 6b and 6c. The recognition of the ground truth traces in Fig. 6a is evident and the complementarity of both the transmitters is clear. In particular, Fig. 6c which covers the upper part FOV proves that G1 and G2 could be detected even beyond the FOV border (40 km). Moreover, several other trajectories can be clearly seen in Fig. 6c.

Another aspect that can be observed in Figs. 6b and c is the high clutter density in the first range cells and at small Doppler frequencies. In these regions, the detectability of the potential targets is low. Only after the tracking and the fusion stage and with the use of the presented a priori information, a good performance can be attained.

6.2 Tracking results

Tracking results involving the whole processing scheme are presented in Figs. 7 and 8 via screenshots of the scenario for four successive time instants out of a 2 h trial. The transmitters, the receiver and the corresponding illumination sectors are displayed according to Table 1. In scenario 1 (Fig. 7a), the start of a scenario with three vessels is displayed. Ground truths G1 and G2 move...
parallel, while G₃ is moving at small distance in front of them. These three targets are represented by tracks T₁, T₂ and T₃.

The track corresponding to G₃ is restarted when the target leaves the region of high clutter (Fig. 7c). At nearly the same time, the AIS signal of G₁ is lost and the grey triangle corresponds to the last known position. However, the track follows the course parallel to target G₂, which is confirmed by GSM measurements. Targets G₁ and G₂ are tracked even beyond the distance of 40 km. Continuous tracks have been achieved over a period of about 2 h.

The results for scenario 2 present a more complex scenario. On the one hand, we look at the ferry traffic between Fehmarn and Rodby (Denmark) and on the other hand, we observe the ship traffic through the Fehmarn Belt (in the orthogonal direction). Targets G₅ and G₆ show two ferries moving in opposite directions. The corresponding tracks show a significant offset to the position of the targets (Fig. 8a). This is due to the region of increased estimation error as discussed in Section 4. The track of G₅ is pursued until arrival at Fehmarn island (Fig. 8c). Target G₁ shows a smaller vessel which casts off from Fehmarn harbour and is moving into the Fehmarn Belt. The track is lost at a distance of about 13 km from the receiver. Targets G₈ and G₉ are two ferries starting at Fehmarn island’s direction. Targets G₇–G₁₀ cross each other in the middle of the Fehmarn Belt. Figs. 8b and c show the scenario shortly before and after the crossing, which is correctly resolved by the tracker with preservation of the track identity. The ship traffic through Fehmarn Belt results in multiple continuous tracks (T₃, T₄, T₇, T₁₀, T₁₁).

7 Conclusions

This paper presented concepts and results of a GSM-based PCL system for maritime surveillance. This system provides simultaneous reception of multiple dislocated BTS’s and allows fusion of data from multiple bistatic configurations. We analysed by theoretical tools the influence of the multistatic Tx–Rx configuration and demonstrated these effects by the experimental results. The reported first real data experiments showed a significant accuracy improvement in the estimation of the target position. The improvement is mainly because of the following features:

- Multistatic tracking operation alone gives already a significant improvement in accuracy. Also, multiple closely spaced targets could be well resolved in track because of the fine Doppler resolution.
- The fusion gain depends critically on the bistatic geometry of the considered BTS. This underlines the need for software tools for adequate passive radar system configuration [5].
- Incorporation of prior information by a clutter map and geographical information map reduces the number of false tracks, in particular, when operating in dense clutter regions like wind parks and blind zones.

Finally, we could show that the occasional loss of an AIS track can be compensated by GSM PCL tracks. This suggests the application of GSM PCL as a complementary sensor for maritime surveillance.

8 Acknowledgments

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9 References