DSm theory for fusing highly conflicting ESM reports

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Abstract - *Electronic Support Measures consist of passive receivers which can identify emitters coming from a small bearing angle, which, in turn, can be related to platforms that belong to 3 classes: either Friend, Neutral, or Hostile. Decision makers prefer results presented in STANAG 1241 allegiance form, which adds 2 new classes: Assumed Friend, and Suspect. Dezert-Smarandache (DSm) theory is particularly suited to this problem, since it allows for intersections between the original 3 classes. Results are presented showing that the theory can be successfully applied to the problem of associating ESM reports to established tracks, and its results identify when miss-associations have occurred and to what extent. Results are also compared to Dempster-Shafer theory which can only reason on the original 3 classes. Thus decision makers are offered STANAG 1241 allegiance results in a timely manner, with quick allegiance change when appropriate and stability in allegiance declaration otherwise.*

Keywords: Electronic Support Measures, Dezert-Smarandache, Dempster-Shafer, allegiance, fusion.

1   Introduction

Electronic Support Measures (ESM) consist of passive receivers which can identify emitters coming from a small bearing angle, but cannot determine range (although some are in development to provide a rough measure of range). The detected emitters can be related to platforms that belong to 3 classes: either Friend (F=1), Neutral (N=2) or Hostile (H=3), heretofore called ESM-allegiance, within that bearing angle.

In the case of dense targets, ESM-allegiance can fluctuate wildly due to miss-associations of an ESM report to established track. Hence, decision makers would like the target platforms to be identified on a more refined basis, belonging to 5 classes: Hostile (or Foe), Suspect (S), Neutral, Assumed Friend (AF), and Friend, since they realize that no fusion algorithm can be perfect and would prefer some stability in an allegiance declaration, rather than oscillations between extremes. This will heretofore be referred to as STANAG 1241 allegiance, or just STANAG allegiance for short [1].

With this more refined STANAG-allegiance, a decision maker would probably take no aggressive action against either a friend or an assumed friend (although he/she would monitor an assumed friend more closely). Similarly a decision maker would probably take aggressive action against a foe and send a reconnaissance force (or a warning salvo) towards a suspect. Neutral platforms would correspond to countries not involved in the current conflict.

All incoming sensor declarations correspond to a frame of discernment of 3 classes, and several theories exist to treat a series of such declarations to obtain a fused result in the same frame of discernment, like Bayesian reasoning and Dempster-Shafer (DS) reasoning [2, 3] (often called evidence theory). However, when the output frame of discernment is larger that the input frame of discernment, an interpretation has to be made as to what this could mean, or how that could be generated. This is the subject of the next section.

1.1   Some solutions

It should be noted that Bayes theory is implemented in a very complex form in STANAG 4162 [4], and that DS theory is found on board many platforms, such as the German F124 frigates [5], the Finnish Fast Attack Craft Squadron 2000 [6], and the Light Airborne Multi-Purpose System (LAMPS) helicopters of the US Navy [7]. The translation from DS to Bayes can be performed via the pignistic transformation [8], and the result broadcast via tactical data links.

In all these implementations, the emitter detected is first correlated to a platform, and then to an allegiance. According to [9], recognition of a platform can range from a very rough scale (e.g. combatant/merchant) to a very fine one (e.g. name of contact/track), whereas identification refers to the assignment of one of the 6 standard STANAG 1241 identities (for which we adopt the word "allegiance" in this report) to a track. The extra identity is "unknown", which we disregard in this report, assuming that all detected emitters are identifiable.

Therefore, this report investigates an alternative method of achieving STANAG-allegiances, which does not aim to compete with the above implementations, but rather can be seen as an expert advisor to the decision maker. Since Dezert-Smarandache theory was only developed extensively after the publications of the STANAGs, this could not have been foreseen by NATO, and is thus worthy of experimentation.

1.2 An interpretation of STANAG 1241

Dezert-Smarandache (DSm) theory can coherently, with well-defined fusion rules, lead to an output amongst 5 classes, even though the input classes number only 3, because the theory allows for intersections. For example,

• "Suspect" might be the result obtained after fusing "Hostile" with "Neutral", and

• "Assumed Friend" might be the result obtained after fusing "Friend' with "Neutral".

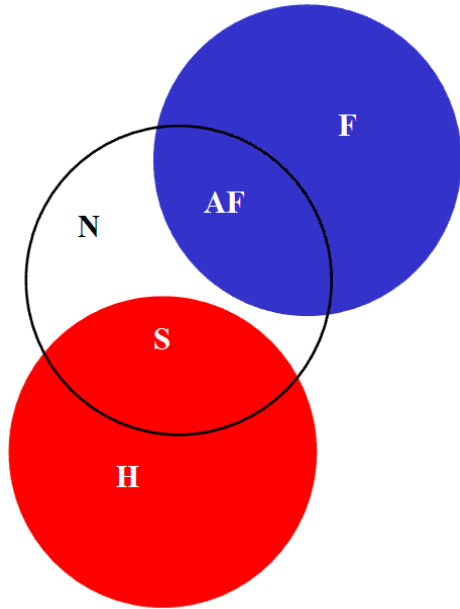This illustrated in the Venn diagram of Figure 1 below.

Figure 1. Venn diagram for the STANAG allegiances.

Note that the set intersection $1 \cap 3 = \emptyset$, the null set, which is a constraint in DSm, leading to the use of its hybrid rule. It also corresponds to the most likely mission for Canadian Forces (CF), namely peace-keeping, or general surveillance, when hostile and friendly forces are not likely to be located close to each other.

1.3 Another interpretation of STANAG 1241

The interpretation in the preceding sub-section is a conservative one, namely that there is only one easy way to become suspect. This could correspond to a decision maker being in a non-threatening situation due to the choice of mission, e.g. peace-keeping. There could be situations where there is a need for a more aggressive response. In the case of a combat mission for example, the appropriate Venn diagram might be the one of Figure 2, where there are many more ways to become suspect, namely all the intersections bordering Hostile.
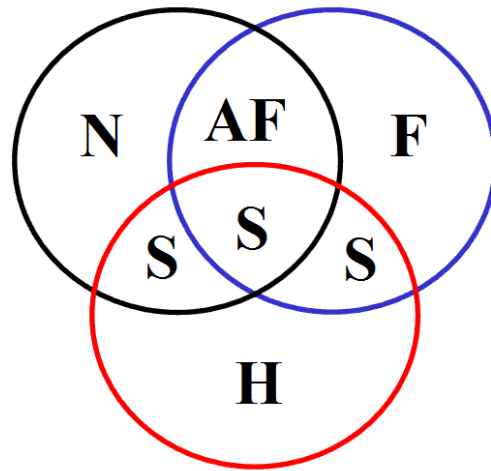
Figure 2. Another possible Venn diagram.

Figure 2 corresponds to a combat situation more appropriate for the USA, or to the CF as long as they play an active role in the Kandahar region of Afghanistan. The situation of Figure 1 will be the one implemented in this paper, as it is more in line with CF roles, and also because all of the features of DSm theory can be exercised, without the additional complexity of keeping all the intersections of Figure 1.

2 Dezert-Smarandache Theory

2.1 Formulae for DS and DSm theories

Since DS theory has been in use for over 40 years, the reader is assumed to be familiar with it [2, 3]. DSm theory encompasses DS theory as a special case, namely when all intersections are null. Both use the language of masses assigned to each declaration from a sensor (in our case, the ESM sensor). A declaration is a set made up of singletons of the frame of discernment Θ, and all sets that can be made from them through unions are allowed (this is referred to as the power set 2^Θ of DS theory). In DSm theory, all unions and intersections are allowed for a declaration, this forming the much larger hyper power set D^Θ. For our special case of cardinality 3, $\Theta = \{\theta_1, \theta_2, \theta_3\}$, with $|\Theta| = 3$, D^Θ is still of manageable size, namely has a cardinality of 19.

In DST, a combined "fused" mass is obtained by combining the previous (presumably the results of previous fusion steps) $m_1(A)$ with a new $m_2(B)$ to obtain a new fused result by applying the conjunctive rule

$$m_1 \oplus m_2(C) = \Sigma\, m_1(A)\, m_2(B) \qquad (1)$$

where $C = A \cap B$, and by re-normalizing by $(1-K)^{-1}$ where K is the conflict corresponding to the sum of all masses for which the set intersection yields the null set. This common renormalization is a critical feature of DS theory, and allows for it to be associative, whereas a multitude of

alternate ways of redistributing the conflict (proposed by numerous authors) loses this property. The associativity of DST is key when the time tags of the sensor reports are unreliable, since associative rules are impervious to a different order of reports coming in, but all others rules can be extremely sensitive to the order of reports. This is the main reason we concentrate only on DS vs. DSm, but another reason is the proliferation of alternatives to DS, which redistribute the conflict in various fashions (for a review, see [10]).

In DSm theory, a constraint like the one that was imposed by Figure 1, namely that $1 \cap 3 = \emptyset$ is treated by the hybrid DSm rule below:

$$m(A) = \phi(A) \, [\, S_1(A) + S_2(A) + S_3(A) \,] \qquad (2)$$

The reader is referred to a series of books [10, 11] on DSm theory for lengthy descriptions of the meaning of this formula (note that the function ϕ is not to be confused with the empty set). A three-step approach is proposed in chapter 5 of [11], which is used here.

If the incoming sensor reports are in DS-space: Friend (F=1), Neutral (N=2) or Hostile (H=3), then Figure 1 has the interpretation in DSm space (allowing intersections during the fusion step) of:

$$\text{Friend} = \{\theta_1 - \theta_1 \cap \theta_2\}$$

$$\text{Hostile} = \{\theta_3 - \theta_3 \cap \theta_2\}$$

$$\text{Assumed Friend} = \{\theta_1 \cap \theta_2\}$$

$$\text{Suspect} = \{\theta_2 \cap \theta_3\}$$

$$\text{Neutral} = \{\theta_2 - \theta_1 \cap \theta_2 - \theta_3 \cap \theta_2\}$$

As expected, all STANAG-allegiances (masses assigned to the sets mentioned above) sum up to 1, as shown below. The left hand side, which is the sum of the masses for all 5 classes, yields the right hand side, which is unity in DSm theory.

$$\theta_1 - \theta_1 \cap \theta_2 + \theta_3 - \theta_3 \cap \theta_2 + \theta_1 \cap \theta_2 + \theta_2 \cap \theta_3 + \theta_2 - \theta_1 \cap \theta_2 - \theta_3 \cap \theta_2 = \theta_1 + \theta_2 + \theta_3 - \theta_1 \cap \theta_2 - \theta_3 \cap \theta_2 = 1 \qquad (3)$$

(since $m(\theta_1 \cap \theta_3) = 0$, i.e. $\theta_1 \cap \theta_3 = 1 \cap 3 = \emptyset$ by Figure 1).

2.2 A typical simulation scenario

In order to compare DS with DSm, one must list the pre-requisites that the scenario must address. It must:
- be able to adequately represent the known ground truth
- contain sufficient miss-associations to be realistic and to test the robustness of the theories
- only provide partial knowledge about the ESM sensor declaration, which therefore contains uncertainty

- be able to show stability under countermeasures, yet
- be able to switch allegiance when the ground truth does so

The following scenario parameters have therefore been chosen accordingly:
- Ground truth is FRIEND for the first 50 iterations of the scenario and HOSTILE for the last 50.
- the number of correct associations is 80%, corresponding to countermeasures appearing 20% of the time, in a randomly selected sequence.
- the ESM declaration has a mass (confidence value in Bayesian terms) of 0.7, with the rest (0.3) being assigned to the ignorance (the full set of elements, namely Θ).

The last 2 bullets of the first list would translate into stability for the first 50 iterations and eventual stability for the last 50 iterations, after the allegiance switch at iteration 50.

This scenario will be the one addressed in the next section, while a Monte-Carlo study is described in the subsequent section. Each Monte-Carlo run corresponds to a different realization using the above scenario parameters, but with a different random seed. The scenario chosen is depicted in Figure 3 below.
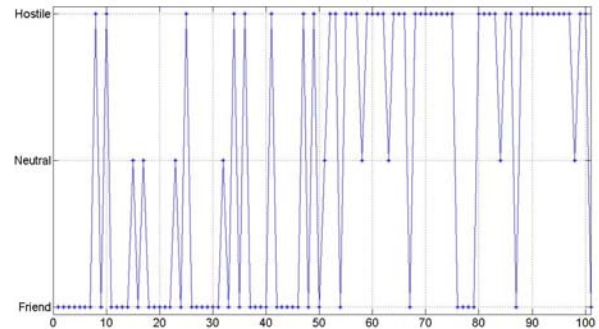

Figure 3. Chosen scenario.

The vertical axis represents the allegiance Friend, Neutral, or Hostile. Roughly 80% of the time the ESM declares the correct allegiance according to ground truth, and the remaining 20% is roughly equally split between the other two allegiances. There is an allegiance switch at the 50th iteration, and the selected randomly selected seed in the above generated scenario generates a rather unusual sequence of 4 false Friend declarations starting at iteration 76 (when actually Hostile is the ground truth), which will be very challenging for the theories.

3 Results for the simulated scenario

Before presenting the results for DS, it should be noted that the original form of DS tends to be overly optimistic. Given enough evidence concerning an allegiance, it will be very hard for it to change allegiances at iteration 50. This is a well-known problem, and a well-known ad hoc solution

exists [12], and consists in renormalizing after each fusion step by giving a value to the complete ignorance which can never be below a certain factor (chosen here to be 0.02). Comparison will be made with DSm and the Proportional Conflict Redistribution (PCR) #5 (PCR5) preferred by Dezert and Smarandache [10].

3.1 DS results

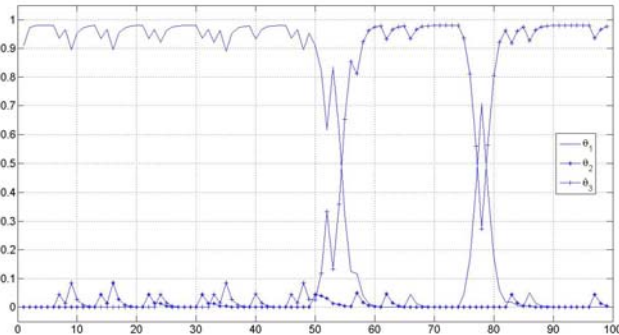The result for DST is shown in Figure 4 below with Friend (1), Neutral (2) and Hostile (3).

Figure 4. DS result for the chosen scenario.

DS never becomes confused, reaches the ESM-allegiance quickly and maintains it until iteration 50. It then reacts reasonably rapidly and takes about 6 reports before switching allegiance as it should. Furthermore after being confused for an iteration around the sequence of 4 Friend reports starting at iteration 76, it quickly reverts to the correct Hostile status.

Note that a decision maker could look at this curve and see an oscillation pointing to miss-associations without being able to clearly distinguish between a miss-association with the other two possible allegiances. This fairly quick reaction is due to the 0.02 assigned to the ignorance, which translates to DS never being more than 98% sure of an ESM-allegiance, as can be seen by the curve topping out at 0.98. Figure 4 shows the mass, which is also the pignistic probability for this case, with the latter being normally used to make a decision.

3.2 DSm results

For the hybrid DSm rule [10], it was suggested to use the Generalized Pignistic Probability in order to make a decision on a singleton belonging to the input ESM-allegiance. This seems to cause problems [13]. Since the whole idea behind using DSm was to present the results to the decision maker in the STANAG allegiance format, the result of Figure 5 would be shown to the decision maker.
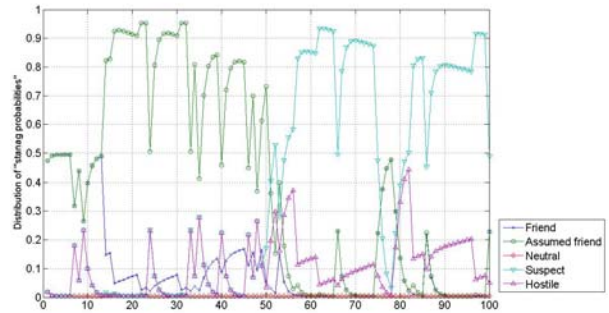

Figure 5. DSm result for the chosen scenario.

The decision maker would clearly be informed that miss-associations have occurred, since Assumed Friend dominates for the first 50 iterations and Suspect for the latter 50. DSm is more susceptible to miss-associations than DS (the dips are more pronounced), but it has the advantage of giving extra information to the decision maker, namely that the fusion algorithm is having difficulty with associating ESM reports to established tracks.

Just as for DS, the Friend declarations starting at iteration 76 cause confusion, as it should. The change in allegiance at iteration 50 is detected nearly as fast as DST. What is even more important is that F and AF are clearly preferred for the first 50 iterations and S and H for the last 50, as they should.

3.3 PCR5 results

PCR5 shows a similar behaviour, but is much less sure of what's going on (the peaks are not as pronounced), as seen in Figure 6. Again, F and AF are clearly preferred for the first 50 iterations and S and H for the last 50, as they should.
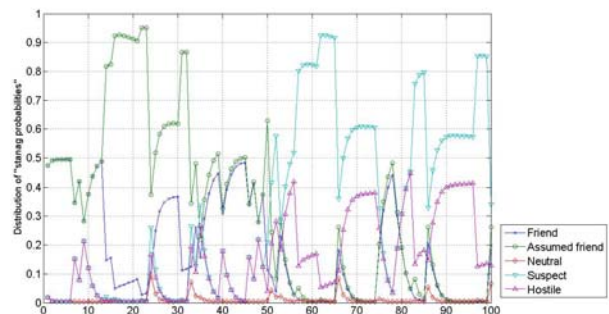

Figure 6. PCR5 result for the chosen scenario.

3.4 Decision-making threshold

Because of the occasionally oscillatory nature of some combination rules, one has to ask oneself when to make a decision or recommend one to the commander. This is illustrated in Figure 7 for DS although the same is

applicable for all the others. A threshold at a very secure 90% would result in a longer time for allegiance change, and result in a longer period of indecision around iteration 76, compared to one at 70%.
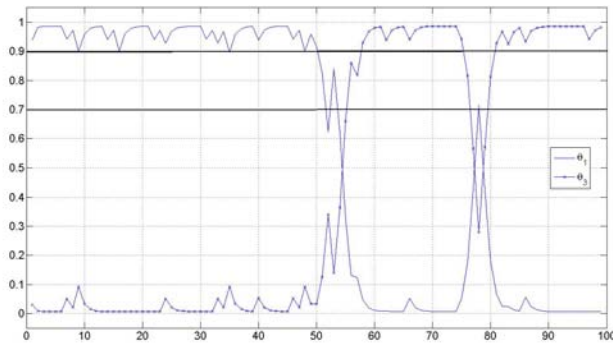

Figure 7. Decision thresholds.

4 Monte-Carlo results

Although a special case such as the one described in the previous section offers valuable insight, one might question if the conclusions from that one scenario pass the test of multiple Monte-Carlo scenarios. This question is answered in this section.

In order to sample the parameter space in a different way, the simulations below correspond to 90% correct associations (higher than the previous 80%), an ESM confidence at 60% (lower than the previous 70%) and an ignorance threshold at 0.02 as before. The number of Monte-Carlo runs was set to 100.

4.1 DS results

The result for DS is shown in Figure 8. As expected, since DS reasons over the 3 input classes, Suspect and Assumed Friend are not involved.
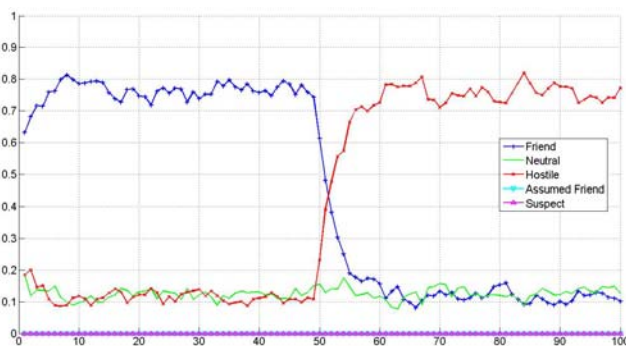

Figure 8. DS result after 100 Monte-Carlo runs.

Naturally, since Assumed Friend and Suspect do not exist in DST, these are calculated as zero. Friend, Neutral, and Hostile have the expected behaviour. One sees the same

response times, after an average over 100 runs, as was seen in the selected scenario of the previous section.

4.2 DSm results

The similar result for DSm is shown in Figure 9 below. In this case, AF dominates for the first 50 iterations, on average (over 100 runs) and S for the last 50, confirming that the chosen scenario was representative of the behaviour of DSm. The response times are similar on average also. DSm is slightly less sure (plateau at 70%) than DS (plateau at 80%), but this can be adjusted by lowering the decision threshold accordingly.
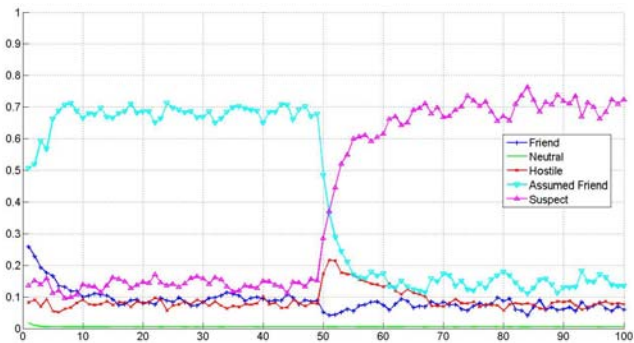

Figure 9. DSm result after 100 Monte-Carlo runs.

4.3 PCR5 results

Finally, the PCR5 result is shown in Figure 10 below. In this case also, AF dominates for the first 50 iterations, on average (over 100 runs), and S for the last 50, confirming that the chosen scenario was representative of the behaviour of PCR5. The response times are similar on average also. PCR5 is slightly less sure (plateau at 60%) than DST (plateau at 80%) or DSmT (plateau at 70%).
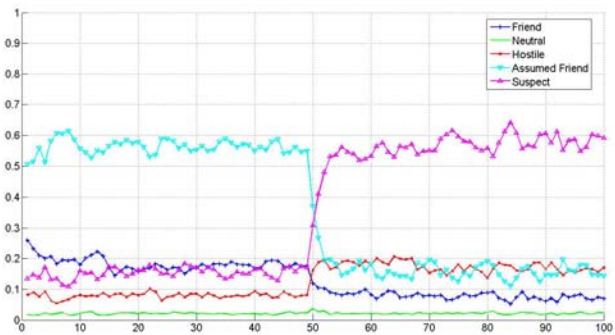

Figure 10. PCR5 result after 100 Monte-Carlo runs.

4.4 Effect of varying the ESM parameters

In order to study the effects of varying the ESM parameters, the simulations below correspond to an ESM confidence at 80% (higher than the previous 60%) and an ignorance

threshold at 0.05 (higher than the 0.02 used previously). The number of Monte-Carlo runs was again set to 100.

A filter was also applied to the input ESM declarations over a window of 4 iterations. The filter assigns lesser confidence to ESM reports which are not well represented in the window. More on this sliding window filtering is available in [13]. The idea of such a sliding window has also been studied before with good results for a variety of reasoning schemes [14]. The results are shown in Figure 11 for DS, Figure 12 for DSm and Figure 13 for PCR5. From these figures, one can see the smoothing effect of the filter, but more importantly the all of the conclusions of the previous Monte-Carlo runs, as well as the selected scenario of the previous section hold in their totality.
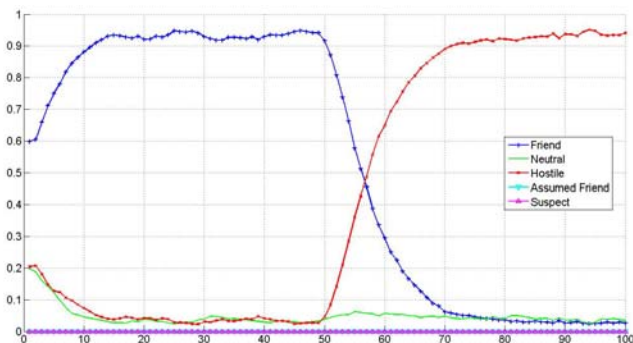

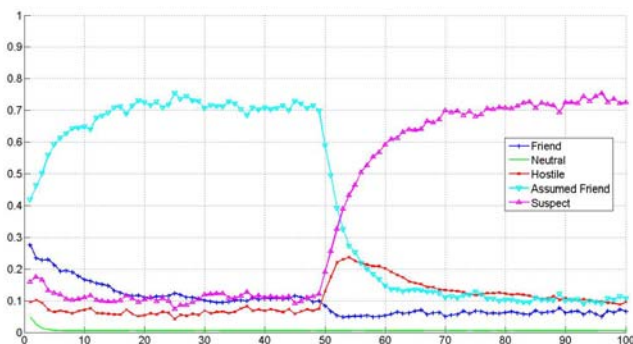Figure 11: DS result after 100 runs and input filter.
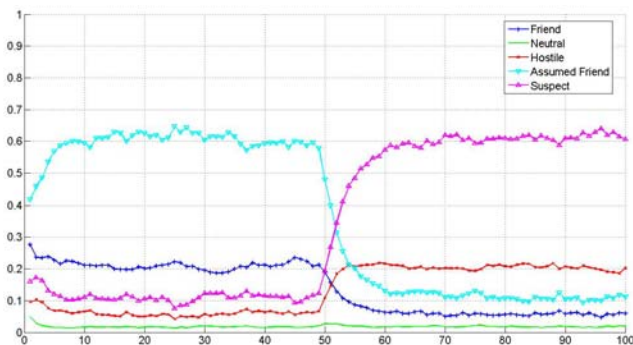

Figure 12: DSm result after 100 runs and input filter.

Figure 13: PCR5 result after 100 runs and input filter.

5   Conclusions

Because of the nature of ESM which consists of passive receivers that can identify emitters coming from a small bearing angle, and which, in turn, can be related to platforms that belong to 3 classes: either Friend, Neutral, or Hostile, and to the fact that decision makers would prefer results presented in STANAG 1241 allegiance form, which adds 2 new classes: Assumed Friend, and Suspect, Dezert-Smarandache theory was used instead, but also compared to Dempster-Shafer theory. In Dezert-Smarandache theory an intersection of Friend and Neutral can lead to an Assumed Friend, and an intersection of Hostile and Neutral can lead to a Suspect.

Results were presented showing that the theory can be successfully applied to the problem of associating ESM reports to established tracks, confirming the work published in [15]. Results are also compared to Dempster-Shafer theory which can only reason on the original 3 classes. Thus decision makers are offered STANAG 1241 allegiance results in a timely manner, with quick allegiance change when appropriate, and stability in allegiance declaration otherwise.

In more details, results were presented for a typical scenario and for Monte-Carlo runs with the same conclusions, namely that Dempster-Shafer works well over the original 3 classes, if a minimum to the ignorance is applied. The same can be said for Dezert-Smarandache theory, and to a lesser extent for a popular Proportional Conflict Redistribution rule, but with the added benefit that Dezert-Smarandache theory identifies when miss-associations occur, and to what extent.

Finally, the effects of varying the input parameters for the performance of the ESM were studied, and all of the conclusions remain the same.

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