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A Methodology for Value of Information Determination in Coalition Sensor Networks

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A Methodology for Value of Information Determination in Coalition Sensor Networks*

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Abstract – A common situation in ISR networks is the establishment of a surveillance area using assets shared from different partners. When the common network needs to be interconnected to the different individual networks of the coalition members, various constraints related to the policies in effect for coalition operations need to be taken into account. These constraints can often be reflected in the metadata associated with the quality and value of information obtained from a sensor network. In order to compute the different parameters associated with the quality and value of information in the context of a coalition operation, we need to have a methodology which can be followed to compute the appropriate metrics In this paper, we use the context of coalition operations to discuss how the QoI and VoI metrics can be calculated.

Keywords: QoI annotation, network fusion, Coalition networks, ISR.

1. Introduction and Motivation

When a coalition partner depends on information from different coalition partners, the level of trust and fidelity associated with the information from other sources could be quite different from its own collected information. The differences can result in modification of the contents of the actual data, or may manifest itself only in the expression of quality associated as a metadata with the information stream.

We use quality of information (QoI) and value of information (VoI) to help measure the degree that the information is useful to the end user. QoI is a measure of the fidelity with which information represents the reality on the ground,. VoI is a measure of the usefulness of the information in the context of a specific application. QoI is expressed as metadata associated with an information stream. A basic framework for specifying the quality of information (QoI) and value of Information (VoI) can be found in [1].

In this paper, we examine a common scenario encountered in coalition operation and discuss how the QoI metadata can be computed. We then discuss how this methodology can be used to solve problems of practical interest in coalition operations, such as planning the route of a UAV or determining the best way to configure a network or reconfigure a network in the case of disruptions and failures.

The next section of this paper describes the scenario of coalition operation that we consider for computation of QoI. In Section III, we describe the methodology by which the value of monitoring any space in the scope of the coalition network can be determined. Section IV provides some practical applications of this methodology. Finally in Section V, we demonstrate how the methodology can be mapped to a generic framework for QoI and VoI metadata calculation.

2. Coalition ISR Network Scenario

We envision a scenario where the U.S. and U.K. are operating in a third nation (e.g. Holistan [4]) as part of a joint coalition operation. Both the U.S. and the U.K. have established their individual base camps in adjacent areas somewhat distant from each other, and have laid out their own ISR networks which are able to detect and monitor any activity happening within the boundaries of their base camp respectively or threats from some distance. The country they are operating in, Holistan, is neutral -- although friendly to both the U.S. and U.K., some elements of Holistan cannot be completely trusted.

Close to the two base camps, there is a large mountainous terrain which is known to be used as a path for transfer of goods and materials by insurgents. The terrain also provides ample opportunity for the insurgents to launch attacks on the base camp. In order to disrupt the supply path for insurgents, and to prevent potential attacks, both of the militaries have come to the conclusion

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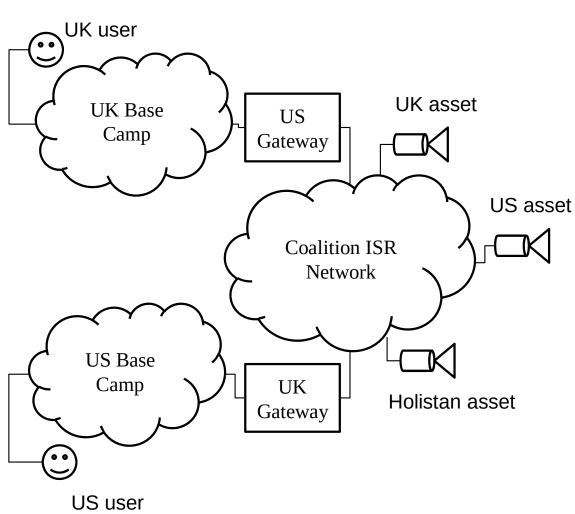
that they need to establish a coalition ISR network between their base camps which can track and monitor activities better.

Both countries have their own assets of cameras and acoustic sensors that they use intend to set up in this area with direct feeds back to their own base camp and forward information to the other. The host country Holistan, operating in close collaboration with the two armies, has also offered some of its ISR assets to be used in the monitoring network. Since the sensors are of different nature with differing resolution and under control of different organizations, the information feeds coming from the coalition network are not all considered equally reliable.

Policy issues are significant in the operation of such an ISR network [5] when information flows between different domains of coalitions and individual partners. The coalition ISR network in itself would be developed in accordance with prevailing technologies, as described in [2],[3] and [6].

A diagrammatic representation of the coalition network is shown below. We assume that a variety of sensor assets are deployed, drawn from the inventories of the coalition partners to monitor the coalition network. The information monitored by the assets reaches the individual base camps through gateways that are controlled by the coalition partners. The feeds to their partner may not be the same information that they receive for a variety of reasons. A primary reason is that of trust. The partners have a small degree of loss of trust with their partner organization because they do not have the same control as they do within their own organization for comprising the data. Even more important in this scenario, since the communications will be travelling outside their base camp boundaries there is some fear that the information can be compromised by spies in the host country.



In order to process the data that is originating from the coalition network, the information is annotated to have a QoI metadata when it is received at the coalition base-camps. The QoI metadata describes the level of fidelity or trust on the information that is obtained from the different sources. One of the functions performed by the US and UK gateways shown above is the annotation and assessment of QoI metadata. That is, the U.S. can assess its own level of thrust on information received from its partner and vice versa. A VoI is also added after further fusion with other information and the measure of fidelity defined below.

When the information is needed and used for specific applications, e.g. to plot the path for a UAV which will need to fly over the space of coalition ISR network, the information needed would be assessed according to the additional value it provides. The value of information is determined on an application-specific basis. That determination of value is made by the receiver of the information, e.g. the U.S. user shown in the figure above.

3. Methodology for Value of Monitoring

In order to introduce the methodology for the value of monitoring any point in the coalition ISR network, we assume that each such point that can potentially be monitored is under observation by some number of sensors. Each such sensor is owned by one of the coalition partners, and follows a specific network topology when communicating with one of the base gateways. We associate with each point $\boldsymbol{p}$ in the space being monitored by the coalition ISR network a function $\boldsymbol{M(p)}$ which is a measure of the fidelity with which the events happening at the point $\boldsymbol{p}$ can be reported to a user. The fidelity is a composition of the information being reported by the different assets that are observing the specific point.

From the perspective of the US gateway (or equivalently from the UK gateway), the fidelity metric itself is a composition of three independent components, a measure of the faithfulness that one can place on the device i at a point based on its position and its internal characteristics, a measure of the trust placed in the owner of the ISR device, and a measure of the path taken for the information from the device to the gateway. We represent these as three other functions, $\boldsymbol{I_i(p,q)}$ is the faithfulness by which a device placed at a point $\boldsymbol{q}$ measures the events happening at point $\boldsymbol{p}$, $\boldsymbol{T_i(m)}$ is a function measuring the trust of the US gateway on the owner of the device, and $\boldsymbol{Q_i(q)}$ is a measure of the quality of information degradation that is obtained due to the path taken by the information from a device located at point $\boldsymbol{q}$ to reach the gateway.

Therefore, we can represent $\mathbf{M_i(p)}$ for a device i owned by a coalition member m and located at a point $\boldsymbol{q}$ as a three-tuple:

$\boldsymbol{M_i(p)} = \{ \boldsymbol{I_i(p,q), T_i(m), Q_i(q)} \}$

If a point is being observed by two ISR assets, the first one with a fidelity measure of $\boldsymbol{M_1(p)}$ and the other with the fidelity measure of $\boldsymbol{M_2(p)}$, then the fidelity of the composed information stream from the two assets will be given by an operation Φ, where the overall fidelity of the composed information stream is given by the $\boldsymbol{M_1(p)}\ \Phi\ \boldsymbol{M_2(p)}$. The fidelity of composed information from multiple ISR assets can be similarly composed. The fidelity is a measure of the QoI for the coalition partner.

Once we have selected the appropriate functions ***I, T,*** and ***Q*** along with the composition function, the fidelity of any observation made by the coalition ISR network at any point can be determined. In the next section, we look at one possible set of functions selection and the composition of the fidelity of observation that can result from this methodology.

For a specific example where the functions associated with the different components of the monitoring of a point are expressed as specific mathematical functions, let us consider the case of monitoring a point in a coalition ISR network where the ISR assets consists of cameras monitoring a region outside both base camps. In this case, representation of the different functions could be:

$\boldsymbol{I(p,q)} = e^{-|\boldsymbol{p}-\boldsymbol{q}|}$ when $|p-q| < r_0$, and 0 otherwise,

where $|p-q|$ is the absolute distance between the points ***p*** and ***q***.

Other more realistic but complex functions can be developed which model the function ***I***. As an example, one can associate a coverage metric ***c*** associated with any point p in the region such that ***c(p)*** measures the number of ISR assets that are monitoring the point. In that case, one can defined ***I(p.q)*** to be 1 if c(p) exceeds a threshold and zero otherwise. A common case in practice would be the situation where a point which is observed by three assets can be triangulated with a reasonable degree of fidelity, but the information is not useful if it is not observed by at least three assets.

Let us define ***T(m)*** as taking the values of 1, 2 and 3, where 1 represents the highest level of trust and used for the ISR assets belonging to the same member who is operating the gateway to the base camp, 2 representing a medium level of trust and associated with assets owned by other members of the coalition and 3 for a lower level of trust (e.g. to assets belonging to Holistan).

And we can define the quality of service offered by a sensor located at a point ***q*** by means of the delay, delay jitter and loss rate of the network connecting the sensor to the gateway. These properties would be computed over the actual network used to interconnect sensor assets, and can be computed easily using standard graph algorithms once this network.

One example of the composite operation Φ would be to compute the average of all the components at any point. In other words, when the fidelity of a point is to be computed by combining the information from different assets, the fidelity of the combined stream is computed by averaging the individual components of the three-tuple. The Φ function could be highly non-linear as well. For example, if one wants to find the location of a signal, each sensor'fidelity value could be near zero but the composite could be high.

Once these functions are determined, the US and UK gateways can annotate the different components of the fidelity description and forward them for use by the respective users of the network.

4. Potential Applications

In some situations, it is possible to convert the fidelity metrics into a total order by computing a formula among the different components. With any definition of the different constituent components, a partial order can be defined on the fidelity of observation at any point. The partial order can be defined on the three-tuples using the following relationship between $M_1 = \{I_1, T_1, Q_1\}$ and $M_{12} = \{I_2, T_2, Q_2\}$ by

$$M_1 < M_2 \text{ if } (I_1 < I_2\ \&\ T_1 \le T_2\ \&\ Q_1 \le Q_2) \text{ or } (I_1 \le I_2\ \&\ T_1 < T_2\ \&\ Q_1 \le Q_2) \text{ or } (I_1 \le I_2\ \&\ T_1 \le T_2\ \&\ Q_1 < Q_2),$$

The partial ordering allows the comparison of some of the fidelity attributes. Furthermore, it also allows for a comparison of the relative fidelity (or QoI) of different attributes, and thus enable the comparison of the metrics that are composed together. A partial distance metric can also be defined on this partial order, which is valid for any pair of comparable metrics. In these cases, the fidelity is converted to a single metric. For a simplified treatment of the potential applications, we will treat the fidelity metric as a single numeric value. However, all of these applications can be converted to operate when only a partial order on the fidelity is described.

Once a fidelity metric is defined, that metric can be used for several potential applications. As an example, consider the planning of the route of a UAV which can fly over occasionally over the area that is under surveillance by the coalition ISR network. The increase in fidelity of any point when the UAV flies over there can be measured by computing the difference (or the partial distance) between the fidelity with and without the information provided by the UAV. Given a constraint for example, on the total fuel available for the UAV, which dictates the maximum length of the path, the optimal path for the UAV would be the path of that length that maximizes the increase in fidelity over the points that the UAV surveys. Such a path can be determined using the Calculus of Variations.

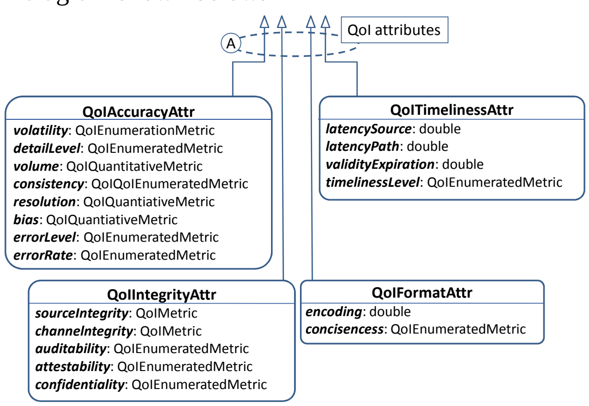
Another application of the fidelity metric can be made to solve sensor coverage problems and initial planning of sensor placement. When an incremental change in the deployment of an existing sensor network needs to be done, the point can be selected which maximizes the increase in overall fidelity of the area being monitored. This allows the placement of new sensors in an area so as to maximize the observed fidelity in a coalition environment when taking into account the differences in trust and communication channels quality that exists among the coalition partners and ISR assets.

Yet another application of the fidelity metric is to provide a way to annotate the metadata that represents the quality of information and the value of information. Such an annotation can be used by the gateways to tag the information received from the different sources in the coalition network. In the next section, we show how the quantified measures of fidelity fit within the framework of QoI and VoI developed within the ITA research program.

5. QoI and VoI Models

In order to describe how the quality of information and value of information is obtained in this scenario, we use the base Metadata model that has been developed in [1]. The base metadata model provides for a general framework and a set of base classes for defining quality of information and value of information. For each specific scenario and application usage context, one can customize the model to meet the specific requirements of the scenario.

The base QoI is characterized as a collection of attributes which are grouped into various classes. Additionally, the base QoI metadata model provides for definition of context and other details which can be found in [11]. The collection of QoI attributes is according to the UML diagram shown below.



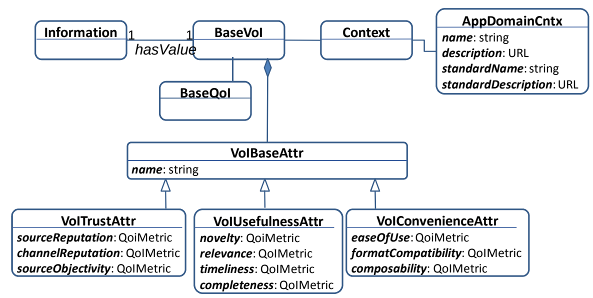
The four categorizations of the QoI attributes are in terms of accuracy, integrity, timeliness and formatting. Towards that goal, the methodology that we have provided measures some of those attributes in terms of the quantifiable attributes of the system.

The function ***I(p,q)*** would have constant parameters that would determine the various values associated with the accuracy attribute. On the basis of the device type that is deployed, the parameters of the function I would determine attributes such as volatility, resolution, bias, errorLevel and errorRate. The data stream that is generated would determine the attributes of detail and volume.

The QOITimeliness attributes are characterized by the parameters of the function ***Q***. This determines the channel properties related to quality of service, and is a key component in determining the timeliness of the information that is received.

The integrity attributes are determined by the function T. Some aspects such as trustworthiness of the channel may be reflected in the definition of the function Q.

The fidelity function M itself can be viewed as quantification of the different attributes that are captured in the value of information field. In the base VoI model that is developed, the value of information is characterized by three groups of attributes, trust, usefulness and convenience. The trust attributes are measured by the function T. In our particular scenario, the trust metric in QoI and the trust metric in VoI are identical.



The usefulness attribute is measured by the function ***M***. The novelty attribute in the field of monitoring information provided at any point is provided by the change in the value of ***M*** which happens when a new piece of information is added in. The relevance and completeness metrics are not used in our scenario.

Thus, the methodology that we have described in this paper can be used to flesh out the details of the base QoI and VoI metadata model in the context of coalition ISR operations.

6. Conclusion

In this paper, we have presented a methodology for determining the value of new information streams that can be obtained by the observation of an area in the context of a coalition ISR network. We have provided for a mathematical representation of different components used in the methodology. We have also shown how the proposed methodology can be used in conjunction with the QoI and VoI metadata models developed in the context of the ITA program.

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