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Sensor Service Selection through Switch Options

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Abstract—Service-oriented Architecture **(SOA) for sensor network applications aims at providing composable sensor network services supporting functionality within a specific application domain together with tools for service composition, so more complex functionalities can be composed of component services. In a distributed environment, such a scheme works by having a given component service choose other components that provide the data that it needs to perform its service. In this paper, we propose to use real options theory for selecting component services. Real options are designed to reduce the risk associated with an investment by delaying the investment decision for a certain period of time or by allowing for the substitutions of initial investment. Thus, they enhance managerial flexibility and add to the overall value of a project but at the same time they incur certain costs. It is natural to think about activated services as investments, and we apply the switch options subset of the real options methodology to manage the risks of high cost that may result from the low reliability of sensors and sensor networks. Furthermore, we compare our approach with several service selection methods and show the advantage of the option-based methodology.**

Keywords- **sensor networks; service-oriented architecture; service modeling; service selection; real options; switch options;**

I. INTRODUCTION

Wireless sensor networks (WSNs) consist of wirelessly communicating sensor nodes that monitor the physical surroundings in which they are deployed, perform in-network processing on the raw measurements that they collect and relay the intermediate processed data to the base station(s) for further analysis and storage. Due to their versatility and re-programmability, WSNs are suitable for implementing ad-hoc, low-cost information collection systems for remote monitoring applications with long-term execution requirements. A Service-oriented Architecture (SOA) approach [1] to designing such monitoring applications decomposes them into a set of software services, each of which provides a well-defined functionality and might be deployed on one or more sensor nodes. These services are assembled into information flow graphs that describe the overall monitoring application. In our previous work [2], we proposed a model for describing sensor services, as well as a methodology for automatically connecting them to produce a *composite* one that satisfies user requirements with respect to the output data that it produces. Additionally, the methods in [2] work to minimize the total cost of the component services that are selected for the composition.

Service selection is based on the assessment of the processing and communication costs that are incurred when a service instantiation in a given sensor node is chosen as part of a composition graph. There were methods proposed for making an efficient choice of operator for general distributed computations (e.g. [3][4][5][6]). However, in addition to focusing on a single cost metric such as energy or delay, prior work has not taken into account *the operational uncertainty* arising in sensor network deployments, which directly affects any estimates of service costs.

Operational uncertainty in sensor networks arises from several causes, including (a) a lack of accurate knowledge of the computational and communication resources of sensor nodes and their residual energy that gets depleted over time, (b) changes in the environmental conditions in which nodes are operating, such as background noise that affects the quality of sensor readings (e.g. audio signals), and (c) the changes in the Value of Information (VoI) that the output of a composite service carries for a particular user at a given point in time. Most dynamic service composition approaches that have been proposed in the literature take account of changing service costs but do not consider the uncertainty arising when estimating these costs. Such additional information can be exploited to further improve the service selection process, leading to more stable composition graphs that exhibit lower overall costs in the long term.

In this paper, we propose the use of *real options* theory for mitigating the risk arising from cost uncertainty that is inherent in a sensor service selection process which might result in a service composition graph soon rendered invalid due to changes in the operating sensor network environment.

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Real options [7] have been used in finance as an instrument for making investment decisions under uncertainty and incomplete information. A particular form of real options called *switch options* allows for explicit modeling of the value of a flexible design for a firm or manufacturing system[1] with a built-in capability of switching among alternative "modes of operation" in response to changing market conditions [7]. The managerial flexibility afforded by such flexible design to quickly adapt to changing market conditions might in the long run outweigh the potentially higher initial investment cost of implementing it. We leverage this decision-making instrument and draw a direct analogy to our service selection problem at hand: by assessing the costs associated with multiple potential service compositions (each of which satisfies user requirements) we can decide on the replacement of currently running services with new and more efficient ones in the future as network conditions change, while minimizing costs in the long term. In summary, this paper makes the following contributions:

- It proposes a metric for quantifying the *value* of choosing a service as a provider of input to another service, which takes account of the value of information, the energy costs, as well as the information delay (between services).
- It introduces a *real options analysis* approach to selecting the input provider services, wherein selected services are considered an investment whose value is measured by the proposed metric, and the risks involved in choosing them are reduced by *periodically re-examining* their selection in view of current network and its environment conditions and switching to a new service composition when necessary. Furthermore, different service compositions examined but not initially selected, are maintained as *switching options* and may be chosen in the future as network conditions change. This method is suitable for long-running sensor applications, for which the initial period of assessing risks is short enough so that the extra costs incurred by this stage is made up by future gains.
- It introduces a novel mathematical model for the value of a switching option for the given switching strategy based on the network and environment measurements made by the currently active sensors and used to signal a switch.
- It evaluates the real options analysis approach to service selection. Our initial results show that the operational uncertainty of sensor networks can be reduced by measuring the network condition changes' impact on service composition costs. Such measurements incur small overhead, but in the long-run the overall cost of providing the composite service is reduced by enabling more efficient component services to be activated as a response to changing network and its environment conditions.

The rest of the paper is organized as follows: in the next section, we sketch the background of the subject of service selection and composition, as well as of real options, with an emphasis on switch options. In the following Section III, we present our method of making service selections through the use of switch options. Evaluation of our methodology is discussed in Section IV. The paper concludes with a discussion of related work in Section V and presentation of conclusions in Section VI, together with suggestions for future work.

II. BACKGROUND

The service selection process operates on a model that describes sensor services and their compositions. This section details the background of the model that is assumed in the rest of this work, and describes the theory of switch options.

A. Service Modeling, Selection and Composition

In [2], a service model based on data flow graphs was proposed for describing interconnected services deployed in sensor networks. Each service description consists of a function that the service applies to a set of allowable, typed input data, producing a set of output data. The service model also includes *metadata* that provides meta-information on the output data that is produced by the service, as well as runtime information (such as costs, fidelity and security properties) of the service deployment.

Based on this model, the *service graph* ($G_S = \{V, E\}$) can be defined as a set of vertices (V) that represent the services, and a set of directed edges (E) between the vertices corresponding to potential information flow amongst them. To satisfy the data input requirements of a given service, the *service selection* process is employed to choose among a plurality of services that can provide input that is compatible (type-wise) with these requirements. The *service composition* problem as further defined in [2] refers to the choice of services and information flows so that a *user request* ($\Phi = \{output_{\Phi,1}, ..., output_{\Phi,n}\}$) can be produced by the resulting composite service. This problem is formulated as follows: For a given $G_S = \{V, E\}$ and Φ, find the $V_C \subset V$ and $E_C \subset E$ with the minimum cost, such that:

$$\Phi \subset \bigcup_{V_i \in V_C} (output\ of\ V_i) \text{ and,}$$

$$\forall\, V_i \in V_C, (input\ of\ V_i) \subset \bigcup_{V_j\ where\ e_{j,i} \in E_C} (output\ of\ V_j).$$

The heuristic approaches described in [2] for solving the above NP-complete problem make use of estimates of the

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[1] As a concrete example, consider a plant that is designed to manufacture multiple products at a possibly higher initial investment cost compared to another that can manufacture only one product with a low initial investment cost. It is clear that a design with more potential choices would be more valuable than one that restricts choices, but the resulting value of flexibility may not be worth the extra cost.

service cost, as communicated through metadata in the service graph.

B. A Brief Introduction to Switch Options

Real options [7] were introduced as an alternative to Net Present Value (NPV)[2] analysis for valuation of investments that provide managerial flexibility in deciding on the course of the investment (e.g., whether to proceed, halt or change plans as more information on the market becomes available) and incorporate knowledge of market conditions in which the investment should take place. The real options approach to investment analysis derives from the use of options contracts in stock market trading. Options contracts provide a kind of insurance against risk. Real options can be used to reduce risk by allowing for the possibility of *deferring* the potential benefits of an investment. For example, a factory may wish to retain the option of tapping multiple suppliers for the raw materials that it needs to manufacture a product, to mitigate the risk of insufficient supplier inventories as demand changes over time, or due to inconsistent quality of the material that suppliers might provide. Option valuation techniques including *Black-Scholes* [8] and *Monte Carlo simulation* methods are often employed to assess the value of real options.

Switch options (for more details, see Chapter 10 in [7]) are a special form of real options that can be used to model the value of keeping multiple alternatives available. This applies to valuing general *process flexibility*, defined as the ability to switch among alternative inputs (for example, switching among various types of fuel that a factory may use for its operation such as oil, natural gas, or electricity), as well as *product flexibility*, which refers to the ability of a factory to manufacture multiple products in response to changing market demands. It is worth noting that in the case where switching costs are absent, exercising the option affects only the current payoff but not any subsequent (switching) decisions, so that the property of option value additivity is preserved.

III. SWITCH OPTIONS AS A SERVICE SELECTION MECHANISM

As the foregoing discussion suggests, switch options constitute a promising modeling and decision making approach for service selections that are made during the service composition process, in the presence of volatile network and environmental conditions. However, the application of this method requires a model for quantifying the value of a service.

A. Quantifying the Value of a Service

The value of a service can be measured by the difference between its benefits and the costs incurred by its execution. The benefit is typically made known through a subjective assessment that results in a user-defined utility, commonly referred to as the *Value of Information* (VoI) [9]. VoI is application-specific and depends on the importance, quality and security of a service's output. On the other hand, costs for accessing a service include any energy spent in processing and communication with the provider of the service, as well as the delay for the transmission of the output that it provides. Hence, the *value* (V) of a service S is:

$$V(S) = V_{\text{inf}}(S) - \alpha(t)E_s(S) - \beta(t)D(S)\ , \qquad (1)$$

where V_{inf} represents the VoI of the output that S produces, E_s represents the energy that is spent by this service, and D is the time it takes for the output of S to reach the requesting service. $\alpha(t)$ and $\beta(t)$ act as unifying parameters for the different units of the above components. They are also application specific and describe the relative importance of energy and delay to the application at a specific point t in time. For example, if the mission becomes time-critical, the β value will increase to penalize the service instances with high delay. Similarly, for services with low energy left in the sensor on which they are implemented, the α value will increase. Furthermore it is entirely possible that the information value ($V_{\text{inf}}(S)$), energy spent ($E_s(S)$) and the delay ($D(S)$) vary during the operation; hence they are also time dependent, although this is not explicitly shown in the equation. In this work we are dealing with a simplified, linear valuation model but other valuation techniques can also be applied, a task that we leave for future work.

B. Switch Options for Service Selection

The value of being able to switch to different operating modes or actions during the development of a project is the extra value that can be gained once the switch is exercised. For example, for two operating modes A and B, of which the former is more valuable at the beginning of the project, the extra value of keeping B as an alternative, as long as there are no switching costs, is $V_{\text{Option}} = \sum_{t=t_0}^{t_n} V_{A\rightarrow B}(t)$, where $V_{A\rightarrow B}(t)$ is the expected value of the extra gain from using B instead of A when market conditions suggest so, and time series $t_0 \ldots t_n$ denotes the times at which the switch was made. Of course, this value is obtained only if choosing B is expected to be more beneficial than keeping A, otherwise the switch will not occur.

The above approach can readily be applied to sensor service selection. However, it becomes apparent that the network and environmental conditions that drive the switching decisions should be assessed before any selection of sensor service instances can take place. We name this task the *test phase*, which is followed by the actual *selection* and *execution* phases. These phases are discussed in the remainder of this section.

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[2] Net Present Value calculates the sum of all future estimated incoming and outgoing cash flows, discounted by the interest rate.

Test phase: once the possible[3] input service providers of a given service have been identified, the test phase of service selection executes them either all at once or one after the other, to estimate the cost that they incur and their delay. The order in which the component services are tested follows the order of dependency that is implicitly specified by service composition graph. The test run lasts for a set period of time, the length of which determines the cost of performing this evaluation. It should be noted that the evaluation is performed for the group of input service providers that had been identified and *not* for all potential service providers in the system. Often, the conditions for switching between the instances may require that the possible input service providers are run all at once.

The cost of a service provider is determined during the test phase by accumulating the energy consumption for processing and communication of the information packets that are relayed along the path that connects the provider and the requesting service. Delay is also estimated in a similar manner. The value of information that is provided by a provider is also assessed at the destination (requesting) service during the test phase, thus the value $V(S)$ (as in Eq. 1) can be computed.

From the above discussion, it is apparent that the test phase (and the service selection method based on switch options described herein) cannot be applied in cases when the composite sensor service is time-critical and short-lived. For example, there is no opportunity to conduct a test phase when one needs to monitor the breakout of a fire in a forest. On the other hand, for long-lived sensor tasks such as temperature or soil contamination monitoring, the costs incurred by the test period are reclaimed by the future gains of switching from one service to another.

The gains from different service options are estimated using the measurements of the test phase as follows. Let $C(t)$ be a random variable representing network and environmental conditions at time t that define *VoI* of options A and B at time t, denoted by $V_A(C(t))$ and $V_B(C(t))$, respectively. Also let I be the random variable representing switching signal to switch from option A to B ($I(t) = 1$) and from B to A ($I(t) = -1$), or no action ($I(t) = 0$), at time t. Most often, the switching signal is a function of $C(t)$, and its quality might depend on which options are active, as only currently active sensors can provide input to the computation of function I. Furthermore, let T denote the duration of the test phase. During that time, we make a series of n measurements of $C(t_i)$ and compute $I(t_i)$, where $t_i = i \times T/n$, as well as $V_A(C(t_i))$ and $V_B(C(t_i))$. Based on these measurements and computations, we create the piecewise linear approximations $v_A(t)$ and $v_B(t)$ of $V_A(C(t_i))$ and $V_B(C(t_i))$ for t in $(0, T)$. Likewise, we create a piecewise constant function $s(t)$ (stating currently active option, either A ($s(t) = 0$) or B ($s(t) = 1$)) defined for $t_i < t \leq t_{i+1}$ as 0 if $i = 0$ (we always start with option A active), or, for $i > 0$, $s(t_i) = \min(\max(I(t_i) + s(t_{i-1}), 0), 1)$, where $\min$ and $\max$ are used merely to keep the result 0 or 1. Then, the benefit per time unit of having an option to switch from A to B is given by the following integral:

$$V(A \to B) = \int_{t=0}^{T} \frac{s(t)(v_B(t) - v_A(t))}{T} dt \ . \qquad (2)$$

If amortization cost per time unit of having option B (which includes cost of switching between options as well as cost of measurements necessary to generate switching signals) is lower than $V(A \to B)$, option B is worth having. If c_{AB} and c_{BA} denote the switching costs from A to B and B to A, respectively, then the switching cost between options A to B normalized over time T is given by the following sum:

$$c(A \to B) = \sum_{i=2}^{n} \frac{I(t_i)}{2T} [(1 + I(t_i))c_{AB} - (1 - I(t_i))c_{BA}] \ .$$

Indeed, when $I(t_i) = 1$, we switch from option A to option B, and when $I(t_i) = -1$, we switch back, so at those times we need to add the cost of switching, and $I(t_i)(1+I(t_i))/2$ yields 1 if and only if when $I(t_i) = 1$, and similarly $-I(t_i)(1-I(t_i))/2$ yields 1 if and only if when $I(t_i) = -1$.

Finally, if the cost of measurements of switching signals at time t is $m(t)$, then the cost of measurements per time unit is:

$$m(A \to B) = \sum_{i=1}^{n} \frac{m(t_i)}{T} \ .$$

Often, $m(t)$ is independent of t, so $m(t) = m_c$ and then $m(A \to B) = \frac{n \times m_c}{T}$.

The above mathematical model captures a direct relationship between the signals used for switching decisions and the value of the switch option. The test phase is required for calibrating the value of switching option and the switching signals. Better these signals are, larger percentage of the benefit of switching to the best solution are. Furthermore, the cost of amortization and achievable benefits of switching determine whether the alternative services are worth keeping.

Service selection and execution phase: once the feasible choices for a set of services are narrowed down based on the lowest estimated cost from the test phase, then the chosen subset of possible input providers are executed and the gains are computed according to Eq. 1, during the service selection and execution phase.

Once conditions for replacement of services are specified, they can be monitored continuously as the operation continues. It should be noted that several conditions calling

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[3] For a service instance to act as a provider to another service, the output data that the former generates must be type-compatible with the input required by the former, while satisfying any conditions based on metadata that is exchanged between the two of them [2].

for a switch may occur at the same time, for example when service values are correlated negatively. Moreover, monitoring of the environmental phenomena may offer information about the kinds of events requiring switching. For example, this could be evident in the case of high humidity being detected during the test phase that affects one service more than another. Knowledge of such a result can be used to switch automatically when humidity increases in the monitored area. Note that such effects depend on the environment in which the sensor network is deployed, making the test phase essential. Furthermore, to be able to switch between services, it is not necessary to run all services during the execution phase. The environmental conditions that are necessary to decide on switching are monitored separately (which constitutes a cost as given in the above mathematical model). The switching points however are *learned* in the *test phase*, where multiple services are run together to see which is more advantageous at which condition. In the following, we illustrate the switch options method with an example of monitoring a covered parking garage.

C. Garage Monitoring Example

Figure 1 shows a sensor network implemented in a covered parking garage. There are two types of services in this network for each area in the garage: (*i*) a microphone service which consists of readings from an acoustic sensor, monitoring the sound volume in the area, and (*ii*) a camera service that provides views of the area covered by the microphone monitors. Note that this is a long term monitoring task during which automated service selection may choose to utilize one or both of the services to monitor each area.

Figure 1. A parking garage example to explain switch options method.

An imaginary set of test period results for this application is given in Figure 2. The test shows how external factors affect the value of the possible services. One might suppose that the camera view for an area will give the best result, but since operating a camera in a long term application such as this is relatively costly (due to energy consumption and maintenance costs), the value of this service must be reduced to account for its cost (see Eq. 1).

Figure 2 shows that when the value of the microphone service drops below a certain level, there is excess noise in the garage, and the value of the camera service increases. Note that excess noise often signifies an important event, hence the value of information (the first factor in Eq. 1) increases even more, giving the camera service a higher value than normal. In contrast, the microphone cannot provide this additional value of information and in fact provides faulty measurements when the noise level is excessive.

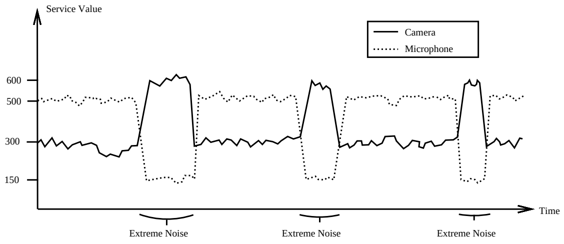

Figure 2. Service value fluctuations for two types of monitoring service.

Once the costs of running multiple services in each area during the test period have been incurred, the service selection mechanism has an option of switching between the microphone and the camera service, and can do it efficiently since it has information (acquired in test phase) about the conditions signaling the need for switching, as well as the correlations of the service values. See Figure 3 for a demonstration of the advantage that could have been gained had switching information been available during the test period in Figure 2. Clearly, the area difference between the curves of Figure 3 and the curve of the microphone service (since it is best on average) in Figure 2 gives us the extra value of the switching option, as given in Eq. 2.

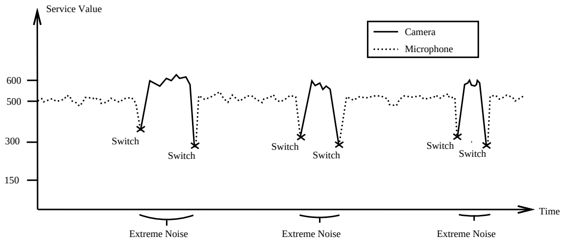

Figure 3. Value of switching option during the test period.

IV. Evaluations

We conduct a simulation-based evaluation of our service selection method via switch options, which is based on the parking garage example described in Section III-C. Our goal is to assess the relative gains in service value obtained by using this new approach compared to the naive method of selecting a service based on its current value, as well as the optimal approach that always has complete knowledge of the value of services in a noisy environment. The setup that we simulate includes a microphone and a camera monitoring service for one area of the parking lot; events triggering system responses are set up to investigate how the service value of the microphone or camera changes. A test period was established to measure the switch points according to the sound levels in the environment. These levels are hence associated with the signaling function $I(t)$, as given in Section III-B. Here, $C(t)$ (i.e. the environmental conditions) is the sound level in the system at time t. This can be measured by both the microphone and the camera service, since we assume the camera service also encapsulates a microphone; hence the conditions of the environment can be measured by the chosen service during execution phase. This allows for the chosen service signal that it should be switched with the other alternative during execution. In another application with different environmental indicators, extra effort may be needed to monitor conditions which signal the switching of service selections. The cost of this extra effort was also mentioned in Section III-B, which may make keeping the option infeasible if too costly. While we try to make reasonable assumptions regarding the evolution of noise level in our target environment as well as the characteristics of the process that generates events of interest, our goal is not to exhaustively study all possible statistical distributions and their parameters for these components, but rather gain a qualitative understanding of the performance of these strategies. A realistic assessment of the service selection approaches can only be performed in a deployed sensor network, a task that we leave as future work.

Two experiments have been simulated that differ in the magnitude of the noise level that is assumed in the environment. In the first experiment, the results of which are shown in Figures 4 and 5, the simulation time is fixed at 100,000 seconds, and the ratio of the test period to the remainder of the simulation time is varied among the runs, within the range of values that is depicted on the x axis in the figures. We introduce two types of sound level changes to the environment, on top of the ground noise sound level, which is constant with a value of 200. The first type represents an increase in the environmental noise without any actual event of interest taking place (for example no car driving in or out of the parking lot but outside noise due to nearby construction is increasing) and follows a gamma distribution with $k = 10$ and $\theta = 0.5$, leading to a mean of 5 and variance of 2.5. The value is then multiplied by 40 and added to the ground noise sound level. In this type of sound level change, the camera sensor does not provide any additional value of information over the acoustic sensor (microphone). The arrival process of these events follows an exponential distribution, with a mean of 40 seconds of simulated time. furthermore, their duration follows the normal distribution with mean 1 and variance 0.1, multiplied by 20.

The second type of sound level change that we simulate represents a significant event of interest that occurred in the environment, for example detection of car movement in the parking garage. In this second type, the value of information (VoI) of the microphone service does not change, but the camera's VoI increases significantly. This sound level change follows a gamma distribution with parameters $k = 90$ and $\theta = 0.33$ that result in a mean of 30 and variance of 10, which is multiplied by 40 and added to the ground noise sound level. These events occur according to an exponential interarrival distribution, with a mean of 100 simulated seconds. Furthermore, their duration follows a normal distribution with mean 1 and variance 0.1, same as in the previous case.

Following the approach of [10], the value of information (VoI) consists of two components: one that is subjective and describes the utility as assessed by the user, and another one that denotes the objective quality of information (QoI) that data carries. VoI is then represented as the product of these two components. For our experiments, a constant QoI of 0.9 is assumed for the camera sensor, while the microphone has a QoI that changes according to $1 - (\frac{SoundLevel}{1000.0})^2$, which accounts for loss of quality with high sounds. The utility for the camera sensor service is set to 1.0 upon occurence of an event, while for the microphone it is constant at 0.2 when no event of interest occurs. Regarding cost, we set it to 0.45 and 0.15 for the camera and the acoustic sensor respectively, which includes both energy and delay as per Equation 1. The value $V(S)$ of each service is the computed by the simulator as $V(S) = utility \times QoI - cost$ for each time unit.

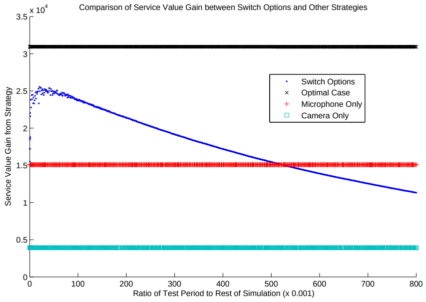

Figure 4. Comparison of Switch Options in Experiment 1 for All Test Period Lengths

In Figure 4, the results for service values corresponding to different lengths of the test phase are given for four strategies: the switch options approach, two strategies that select either the camera or the microphone service exclusively, and the optimal approach that has complete and accurate knowledge of the VoI and the costs. Evidently, choosing either the microphone or the camera service provides less value than switching between them during the system's run time. This is to be expected, since a system that does not make use of the test phase does not know if and when it should switch between alternatives. Such decisions in our experiments are made via the expected value by each service at a given sound level. Although the test phase is indeed useful, as it gets longer, the value gains decrease due to the excess cost of running (and testing) both services. Figure 5 shows the results for an optimal length of the test phase by way of comparing them with shorter ones for the same experiment. From the graph, it appears that when the length is too short (for example only 0.1% of the actual system run time), the gain in value is rather small. This is due to the switching options approach not being able to determine when to make a switch, as a consequence of limited experience with events.

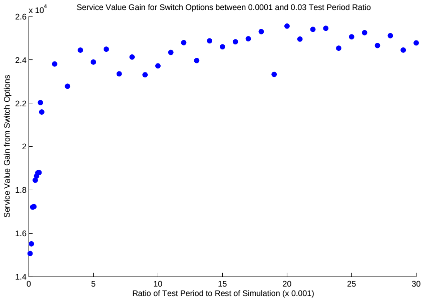

Figure 5. Gain from switch options in experiment 1 for test period lengths up to 0.03 of the rest of simulation period

The second simulation experiment that we ran, named *Noisy Parking Garage*, differs from the previous one in that the magnitude of the first type of sounds level changes (i.e. those that correspond to changes in the ambient noise level of the environment but not to events of interest) exhibit a much higher average. The interarrival times and the other parameters listed previously are kept the same, but now each such sound level change follows a gamma distribution with $k = 40$ and $\theta = 0.5$ (thus mean is 20 and variance 10), which is again multiplied by 40 and added to ground noise sound level of 200 as before. In this configuration, the ambient sound changes are of high magnitude, and due to the decrease in QoI of the microphone service, the total gain from using it is expected to be lower. The results of this simulation setup are presented in Figures 6 and 7.

As it can be seen from Figure 6, the value from the microphone service decreases significantly compared to the previous experiment, while that of the camera service remains the same. This is due to the the higher ambient noise levels of the parking lot that adversely affect the quality of acoustic measurements obtained from the microphone, which decreases its QoI. The overall value obtained through the switch options strategy is similarly decreased, with its peak level becoming lower and the rate of decay higher as the length of the test period increases. Similar results are observed for the value of the optimal service selection.

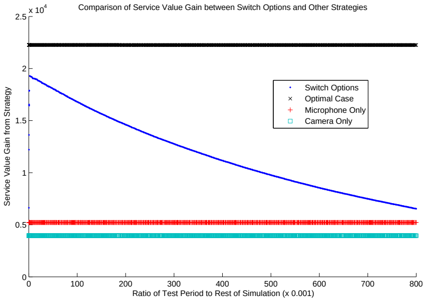

Figure 6. Comparison of switch options in experiment 2 for all test period lengths.

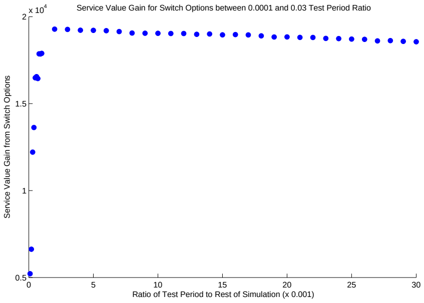

Figure 7. Gain from switch options in experiment 2 for test period lengths up to 0.03 of the rest of simulation period.

Finally, in Figure 7, we examine the service value obtained through the switch options strategy by ranging the test period length from 0.1% to 3% of the rest of the simulation time. The peak value of the switch option strategy is reached when the test period is set to 0.3% of the overall simulation time, at which point the best tradeoff between discerning switching points and keeping costs minimal is achieved for the given simulation settings.

V. RELATED WORK

Prior studies in service selection and composition are either limited in scope or do not consider critical issues in the specific application domain of sensor networks. In more detail, [3] and [4] consider only energy spending, while [5] deals only with load balancing issues. Although [6] does take into account different metrics, possible combinations of them are ignored. Perhaps of greater importance is that *the operational uncertainty in sensor networks* is not considered in the aforementioned related efforts, although in some of the cited works this is a consequence of examining a domain other than sensor networks.

Natural resource investments management is one of the key applications of real options analysis. For example, [11] examines the valuation of offshore petroleum leases.

The authors provide empirical comparisons (through actual industry bids) between real options and pure discounted cash flows (DCF), which is a valuation technique of a project that does not take into account managerial flexibility. Services representing functional units of a company have also been examined in light of real options. [12] proposes the use of real options theory to decide if it is profitable for a firm to reconfigure their service units, e.g., to distribute them, collect them in a central unit, etc.

An exposition of the theory of switching in virtual organization may be found in [13]. Switch options have been applied to the management of different modes of operation (e.g. ability to produce different materials according to market conditions) for investments [14][15]. [14] is one of the first papers examining different modes of production, and utilizes a stochastic dynamic programming approach which encapsulates the value of having the flexibility to switch between these modes. The second paper [15] examines the option to change the quantity of resources used for production, which is due to the uncertainty of the demand for the product.

VI. CONCLUSION

Selecting component services during composition of a complex service in sensor network environment is a complicated undertaking because of uncertainty arising in service activation and execution costs, varying delays in transferring data from one service to another, as well as the ever changing value of information that is obtained from the unreliable and noise-sensitive sensor measurements. This uncertainty needs to be accounted for during the selection process. In this paper, borrowing from the vast economic literature on real options that are used to valuate investments under uncertain market conditions, we propose a method for performing service selection using switch options. The proposed method explicitly models the value of having flexible alternative choices for selecting component services, as conditions in the sensor network environment change dynamically. In this approach, before performing the actual selection, the values and costs of services are estimated during a test phase, in which the most appropriate switching signals are also calibrated. Simulation results are provided to evaluate the performance of the proposed method against the naive approach of static service selection.

Future work includes improvement of our method via online detection of switch points, which is expected to decrease the costs incurred by running services simultaneously. Furthermore we plan to implement the proposed method in a sensor network testbed, and evaluate the advantages of our approach in a realistic sensor application.

REFERENCES

[1] Ibbotson, J., Gibson, C., Wright, J., Waggett, P., Zerfos, P., Szymanski, B. K., Thornley, D. J., *Sensors as a Service Oriented Architecture: Middleware for Sensor Networks*, IEEE Int. Conf. on Intelligent Environments, Malaysia, July 2010.

[2] Geyik, S. C., Szymanski, B. K., Zerfos, P., Verma, D., *Dynamic Composition of Services in Sensor Networks*, IEEE Int. Conf. on Services Computing, SCC, Page(s): 242-249, 2010.

[3] Kalasapur, S., Kumar, M., Shirazi, B. A., *Dynamic Service Composition in Pervasive Computing*, IEEE Trans. on Parallel and Distributed Systems, Vol. 18, No. 7, July 2007.

[4] Park, E., Shin, H., *Reconfigurable Service Composition and Categorization for Power-Aware Mobile Computing*, IEEE Trans. on Parallel and Distributed Systems, Vol. 19, No. 11, Nov. 2008.

[5] Repantis, T., Drougas, Y., Kalogeraki, V., *Adaptive Component Composition and Load Balancing for Distributed Stream Processing Applications*, Peer-to-Peer Networking and Applications, Vol. 2, No. 1, Page(s): 60-74, Mar. 2009.

[6] Alrifai, M., Risse, T., *Combining Global Optimization with Local Selection for Efficient QoS-aware Service Composition*, ACM Int. Conf. on World Wide Web, WWW, Page(s): 881-890, New York, NY, USA, 2009.

[7] Schwartz, E. S., Trigeorgis, L., *Real Options and Investment Under Uncertainty: Classical Readings and Recent Contributions*, MIT Press, Cambridge, 2001.

[8] Black, F., Scholes, M., *The Pricing of Options and Corporate Liabilities*, Journal of Political Economy, Vol. 81, No. 3, Page(s): 637-654, 1973.

[9] Bisdikian, C., Kaplan, L., Srivastava, M., Thornley, D., Verma, D., Young, R., *Building Principles for a Quality of Information Specification for Sensor Information*, Int. Conf. on Information Fusion, Seattle, WA, July 2009.

[10] Chen, L., Szymanski, B. K., Branch, J., *Auction-Based Congestion Management for Target Tracking in Wireless Sensor Networks*, IEEE PERCOM, March 2009.

[11] Paddock, J. L., Siegel, D. R., Smith, J. L., *Option Valuation of Claims on Real Assets: The Case of Offshore Petroleum Leases*, The Quarterly Journal of Economics, Vol. 103, No. 3, Page(s): 479-508, Aug. 1988.

[12] Ning Su, N., Akkiraju, R., Nayak, N., Goodwin, R., *Shared Services Transformation: Conceptualization and Valuation from the Perspective of Real Options*, Decision Sciences, Vol. 40, No. 3, Aug. 2009.

[13] Mowshowitz, A., *Virtual Organization: Toward a Theory of Social Transformation Stimulated by Information Technology*, Quorum Books, Westport, CT, 2002.

[14] Kulatilaka, N., *Valuing the Flexibility of Flexible Manufacturing Systems*, IEEE Transactions on Engineering Management, Vol. 35, Issue 4, Page(s): 250-257, Nov. 1988.

[15] Harrison, J. M., Van Mieghem, J. A., *Multi-Resource Investment Strategies: Operational Hedging under Demand Uncertainty*, European Journal of Operational Research, Vol. 113, Issue 1, Page(s): 17-29, Feb. 1999.