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INFORMATION FUSION AND PERFORMANCE MODELING WITH DISTRIBUTED SENSOR NETWORKS

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George Mason University

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Final Report

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14. ABSTRACT

The focus of this project is to develop and demonstrate the fusion methodologies to enhance the ability to integrate multi-source information and to assess fusion performance for numerous applications such as situational awareness, surveillance, and tracking. The focus of the Year 1 effort was on developing a solid theoretical foundation and on developing autonomous and efficient information fusion algorithms with distributed sensors. The focus of Year 2 effort was to develop a set of fusion performance modeling methodologies based on explicit links of spatial and temporal relationships between target features and sensor observations. We have accomplished the goals. Specifically, we developed a set of scalable fusion algorithms and the corresponding theoretical performance analysis in a dynamic sensor network environment. We have also developed a framework for quantifying the classification performance of a set of sensors with varying qualities based on local confusion matrix and global confusion matrix using Bayesian network model. In addition, we have developed a software tool based on UnBBayes open source environment to test the performance modeling. The resulting methodology has significant potential for applications in high level fusion and situational assessment.

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November 30, 2010

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Attention: Dr. Robert Bonneau

RE: AFOSR Grant #FA9550-08-1-0425

Dear Dr. Bonneau,

Enclosed please find a copy of our final technical report for the grant #FA9550-08-1-0425 for period from Aug. 2008 to Aug. 2010. Thank you very much for your support.

Sincerely,

KC Chang
Professor, SEOR
George Mason University

Final Technical Report #2010-FA9550-08-1-0425

AFOSR Grant #FA9550-08-1-0425

Title: Information Fusion and Performance Modeling with Distributed Sensor Networks

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Abstract

The focus of this project is to develop and demonstrate the fusion methodologies to enhance the ability to integrate multi-source information and to assess fusion performance for numerous applications such as situational awareness, surveillance, and tracking. The focus of the Year 1 effort was on developing a solid theoretical foundation and on developing autonomous and efficient information fusion algorithms with distributed sensors. The focus of Year 2 effort was to develop a set of fusion performance modeling methodologies based on explicit links of spatial and temporal relationships between target features and sensor observations. We have accomplished the goals. Specifically, we developed a set of scalable fusion algorithms and the corresponding theoretical performance analysis in a dynamic sensor network environment. We have also developed a framework for quantifying the classification performance of a set of sensors with varying qualities based on local confusion matrix and global confusion matrix using Bayesian network model. In addition, we have developed a software tool based on UnBBayes open source environment to test the performance modeling. The resulting methodology has significant potential for applications in high level fusion and situational assessment.

This report summarizes our research accomplishments during the performance period from August 2008 to August. 2010.

1. Introduction

Distributed information and data fusion with a suite of sensor systems provide core capabilities to numerous applications such as situational awareness, surveillance, navigation, and tracking. The increasing capabilities and ubiquity of computing technologies and data networks continue to advance information exploitation abilities for combining data from multiple remote sources to produce increased value. In particular, information fusion is a key enabler under development for the United States Department of Defense (US DoD) network-centric Command, Control, Communications and Intelligence (C^3I) capabilities.

To date, the advances in multi-sensor fusion systems have focused on algorithms for tracking and fusion, building design architectures and rules for identifying information duplication (i.e., rumor propagation or double counting), and operation, allocation, and self-calibration of programmed or ad hoc sensor networks.

While researchers in the field of sensor data fusion have advanced significantly during the last decade, these algorithms have been limited for the most part to relatively well-defined network architectures. A unified fusion technique for general sensor networks is yet to be developed. The goal of this effort is develop a solid theoretical foundation and a set of algorithms that can be readily implemented. In particular, we proposed to develop and integrate the four components of research described below:

- A theoretical foundation for networked sensor fusion with arbitrary connectivity and message delays as well as random or non-synchronous local sensing and communication rates while minimizing the amount of data exchanged between agents.

- A set of practical autonomous fusion algorithms and a new methodology for the design and selection of fusion rules, communication architecture, and deployment configuration of distributed sensor networks.

- A general framework for quantifying the operational characteristics of a sensor, a set of metrics for evaluating the operational performance of a sensor network, and evaluating the fusion performance of multiple, asynchronous sensors of varying quality.

- A test and simulation environment to validate and support design of distributed fusion algorithms and performance modeling and to be available for integration into government systems.

2. Project Tasks

The general research tasks for this research as proposed are summarized thus:

- Develop autonomous information fusion algorithms with distributed sensors. The focus is on developing a solid theoretical foundation and a set of scalable and efficient algorithms. We focus on level-1 and level-2 fusion as defined by the DFIG model.

- Develop a set of fusion performance modeling methodologies based on explicit links of spatial and temporal relationships between target features and sensor observations. The focus is on developing Bayesian network modeling and inference algorithms with high level situational assessment.

- Develop test and simulation to validate and support design of distributed fusion algorithms and performance modeling. A main task is to develop metrics for quantifying the performance of the system then apply the metrics to evaluate and compare alternative fusion strategies. The emphasis will be on testing algorithm scalability and real time capability.

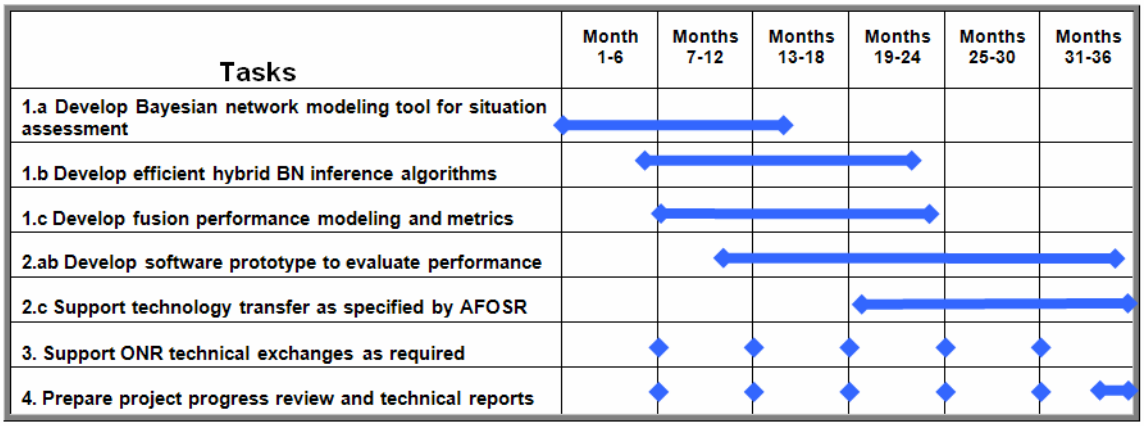
3. Project Schedule and Milestones

The original project schedule and milestones are given in Table 1. The original project Work Plan Schedule is shown in Table 2.

Table 1. Project Schedule and Milestones

Project Tasks and Milestones	
	1. Develop fusion performance modeling methodologies based on explicit links of spatial and temporal relationships between target features and sensor observations. (a) Develop Bayesian network modeling for low and high level situational assessment (b) Develop efficient BN inference algorithms for hybrid models (c) Develop fusion performance modeling and evaluation methodologies with a set of defined performance metrics
	2. Develop methodology and software prototype to validate and evaluate the performance of the fusion system (a) Develop adaptive model resolution and metrics for quantifying the performance of the system (b) Develop MATLAB and Java based test environment to validate performance methodologies (c) Initiate technology transfer to industry or government as specified by AFOSR.
	3. Support the technical exchanges and special studies as required by the AFOSR Program Manager. (a) Attend and participate in technical interchange meetings to discuss technical issues related to the research tasks. (b) Lead and participate in special studies as required. (c) Document and distribute the technical findings and the simulation results as needed.
	4. Management and Reporting. (a) Prepare monthly financial reports and annual technical progress reports. (b) Prepare semi-annual progress review and comprehensive annual technical reports.

Table 2. Original Work Plan Schedule



4. Change in AFOSR Program Manager and Project Scope

The project was started in August 2008. Soon after the project was started, the program manager was changed from Dr. David Luginbuhl to Dr. Doug Cochran in late 2008. After a brief discussion with the PI in summer 2009, the new program manager, Dr. Doug Cochran, felt that the project "is not sufficiently aligned with the scientific direction the AFOSR Information Fusion program is moving to justify continued investment" and decided to terminate the project in July 2009 before a formal annual review which took place in Oct. 2009. The project option was not exercised but a no-cost extension of the effort to August 2010 was subsequently granted by Dr. Cochran. The program manager was changed from Dr. Doug Cochran to Dr. Robert Bonneau in 2010.

Because of the 50% funding reduction of the project due to early termination, we were not able to complete all the tasks as planned in the original proposal. However, we did try our best to accomplish as much technical tasks as we could. The details are described in Section 6.

5. Project Management

This research project was directed by Dr. KC Chang of George Mason University, who devoted 20% of his time during the academic year and six weeks during the summer to this research. The research effort was performed by Dr. KC Chang (PI) together with a research faculty and two graduate students. Specifically,

1. A part-time (25%) research faculty, Dr. Wei Sun, who worked on the development of efficient hybrid inference algorithms and the development of metrics to quantify the overall performance of the systems.
2. A part-time (50%) PhD student, Mr. Rommel Carvalho, who focused on the development of a theoretical foundation and analytical methodology for predicting fusion performance assessments as well as the software development for the simulation environment.
3. A full-time MS student, Mr. Ashirvad Naik, who worked on developing a modeling and simulation environment with MATLAB to support specification and performance evaluations, and the validation of the proposed methodologies with test cases and established benchmark problems.

6. Technical Accomplishments

During the two years effort of the project, we have been developing rigorous mathematical foundation and a set of algorithms for distributed fusion in dynamic networks. In particular, we have accomplished the following:

- A mathematical foundation based on information genealogy for networked sensor fusion with arbitrary connectivity and message delays as well as a set of practical autonomous information fusion and dissemination algorithms. We have documented and published several papers on this area [1-2,8]. The papers were

well received. Specifically, an earlier of the paper [8] published in Fusion 2008 was the runner-up of the best paper award (top 1% of the 300+ papers).

- Complementary multi-level dynamic Bayesian network (DBN) modeling and inference algorithms that provide the infrastructure to aggregate traditional and non-traditional data from disparate sources at each fusion level. In particular, scalable inference in distributed hybrid Bayesian networks is an important area for research but remains a difficult task because of its potentially arbitrary distributions and possible nonlinear dependence relationships between variables. We proposed a unified computing scheme of messages propagating between different types of variables. We have documented and published several papers on this area [4-5,7].
- Performance analysis of a multisensor fusion system modeled by a Bayesian network. Multi-Sensor Fusion is founded on the principle that combining information from different sensors will enable a better understanding of the surroundings. However, it would be desirable to evaluate how much one gains by combining different sensors in a fusion system, even before implementing it. We developed a state-of-the-art tool that allows a user to evaluate the classification performance of a multisensor fusion system modeled by a Bayesian network. Specifically, the results was documented in a paper published in Fusion 2009 [3] which received one of the best student paper awards.
- Mixture distribution representation and metrics for scalable fusion - Mixture distributions have been used in many applications for dynamic state estimation including distributed tracking, and multisensor fusion. However, the recursive processing of the mixture distributions incurs rapidly growing computational requirements. In order to keep the computational complexity tractable and to ensure scalability while trading-off performance, we developed a recursive mixture reduction algorithm with a given error bound. We have documented and published our work in [6,9].

7. Technology Transfer

We have been working with several small businesses to apply our technology to other applications. For example, we have been working with Mr. Mark Frymire and Dr. Chris Smith of Decisive Analytic Corporation to apply the scalable fusion technique we developed in this effort for missile defense application [9]. We have also worked with Dr. Craig Agate of Toyon corporation on applying our fusion techniques for ad hoc UAV sensor networks [10].

8. References

[1] Marty Liggins and K.C. Chang, “Distributed Fusion Architectures, Algorithms and Performance within a Network Centric Architecture,” in Fusion Hand Book, Vol. I, Edited by Marty Liggind and David Hall, Oct., 2008.

[2] KC Chang and Vikas Kotari, “An Epidemic Model for Biological Data Fusion in Ad Hoc Sensor Networks,” in Proc. SPIE Defense and Security Symposium, Orlando, Florida, April, 2009.

[3] Rommel Carvalho and KC Chang, “A Performance Evaluation Tool for Multi-Sensor Classification Systems,” in Proc. 12th International Conference on Information Fusion, Seattle, July, 2009, *Received one of the Best Student paper awards.*

[4] Wei Sun and KC Chang, “Message Passing for General Hybrid Bayesian Networks: Representation, Propagation and Integration”, *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 45, No. 4, pp. 1525-1537, Oct., 2009.

[5] Wei Sun and KC Chang, “Direct Message Passing for Hybrid Bayesian Network and Performance Analysis,” in Proc. SPIE Defense and Security Symposium, Orlando, Florida, April, 2010.

[6] KC Chang, Ashirvad Naik, and Chist Smith, “A comparison of distance metrics between mixture distributions,” in Proc. SPIE Defense and Security Symposium, Orlando, Florida, April, 2010.

[7] Wei Sun, KC Chang, and Kathy Laskey, “Scalable Inference for Hybrid Bayesian Networks with Full Density Estimations,” in Proc. 13th International Conference on Information Fusion, Edinburgh, UK, July, 2010.

[8] KC Chang, Chee-Yee Chong, and Shozo Mori, “Analytical and Computational Evaluation of Scalable Distributed Fusion Algorithms,” *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 46, No. 4, Oct., 2010.

[9] HD Chen, KC Chang, and Christ Smith, “Constraint Optimized Weight Adaptation for Gaussian Mixture Reduction,” in Proc. SPIE Defense and Security Symposium, Orlando, Florida, April, 2010.

[10] Hongda Chen, KC Chang, and Craig Agate, “Tracking with UAV using Tangent-plus-Lyapunov Vector Field Guidance,” in Proc. 12th International Conference on Information Fusion, Seattle, July, 2009.

9. Appendix

Two of the selected papers [4][8] are appended in this report for reference.

Message Passing for Hybrid Bayesian Networks: Representation, Propagation, and Integration

WEI SUN

K. C. CHANG
George Mason University

The traditional message passing algorithm was originally developed by Pearl in the 1980s for computing exact inference solutions for discrete polytree Bayesian networks. When a loop is present in the network, propagating messages are not exact, but the loopy algorithm usually converges and provides good approximate solutions. However, in general hybrid Bayesian networks, the message representation and manipulation for arbitrary continuous variable and message propagation between different types of variables are still open problems. The novelty of the work presented here is to propose a framework to compute, propagate, and integrate messages for hybrid models. First, we combine unscented transformation and Pearl's message passing algorithm to deal with the arbitrary functional relationships between continuous variables in the network. For the general hybrid model, we partition the network into separate network segments by introducing the concept of interface node. We then apply different algorithms for each subnetwork. Finally we integrate the information through the channel of interface nodes and then estimate the posterior distributions for all hidden variables. The numerical experiments show that the algorithm works well for nonlinear hybrid BNs.

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Refereeing of this contribution was handled by T. Robertazzi.

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I. INTRODUCTION

Bayesian network (BN), also known as probability belief network, causal network, [7, 23, 24] is a graphical model for knowledge representation under uncertainty and a popular tool for probabilistic inference. It models dependence relationships between random variables involved in the problem domain by conditional probability distributions (CPDs). In the network, CPD is encoded in the directed arc linking the associated random variables. The random variables that have arcs pointing to other random variables are called parent nodes and the random variables that have incoming arcs are called children nodes. The most important property of the BN is that it fully specifies the joint distribution over all random variables by a product of all CPDs. This is because each random variable is conditional independent of its nondescendant given its parents. Factoring reduces the numbers of parameters representing the joint distribution and so saves the computations for reasoning. One of the important tasks after constructing the BN model is to conduct probabilistic inference. However, this task is NP-hard in general [8]. This is true even for the seemingly easier task of finding approximate solutions [10]. Nevertheless, for some special classes such as discrete polytree or linear Gaussian polytree networks, there exists an exact inference algorithm using message passing [24] that could be done in linear time. In the past decades, researchers have proposed a great number of inference algorithms for various BNs in the literature [12]. They can be divided into two basic groups: exact and approximate algorithms. Exact inference only works for very limited types of networks with special structure and CPDs in the model. For example, the most popular exact inference algorithm—Clique tree [20, 28], also known as junction tree or clustering algorithm [13]—only works for a discrete network or the simplest hybrid model called conditional linear Gaussian (CLG) [18]. In general, the complexity of the exact inference is exponential to the size of the largest clique[1] of the triangulated moral graph in the network. For networks with many loops or general hybrid models that have mixed continuous and discrete variables, the intractability rules out the use of the exact inference algorithms.

For probabilistic inference with hybrid models, relatively little has been developed so far. The simplest hybrid model CLG is the only hybrid model for which exact inference could be done. The state-of-the-art algorithm for exact inference in CLG is Lauritzen's algorithm [17, 19]. It computes the exact answers in the sense that the first two moments of the posterior distributions are correct, while the true distribution might be a mixture of Gaussians. In general, the

[1] A fully connected subnetwork.

hybrid model may involve arbitrary distributions and arbitrary functional relationships between continuous variables. It is well known that no exact inference is possible in this case. However, approximate methods have been proposed [6, 16] to handle different hybrid models. In recent years, researchers also proposed inference algorithms using mixture of truncated exponentials (MTE) [9, 21] to approximate arbitrary distributions in order to derive the close-form solution for inference in hybrid models.

Generally, there are three main categories of approximate inference methods for BNs: model simplification, stochastic sampling, and loopy belief propagation. Model simplification methods simplify the model to make the inference algorithm applicable. Some commonly applied simplification methods include the removal of weak dependency, discretization, and linearization. Stochastic sampling is a popular framework including a number of algorithms, such as likelihood weighting (LW) [11, 27] and the state-of-the-art importance sampling algorithm called adaptive importance sampling (AIS-BN) for discrete BNs [5]. The major issue for sampling methods is to find a good sampling distribution. The sampling algorithm could be very slow to converge or in some cases with unlikely evidence, it may not converge even with a huge sample size. In recent years, applying Pearl's message passing algorithm to the network with loops, so-called "loopy belief propagation" (LBP) [22, 29], has become very popular in the literature. Although the propagating messages are not exact, researchers found that LBP usually converges, and when it converges it provides good approximate results. Due to its simplicity of implementation and good empirical performance, we propose to extend LBP for approximate inference for hybrid model. Unfortunately, because of the differences in representation and manipulations of messages with discrete and continuous variables, there is no simple and efficient way to pass messages between them. In [30], the authors use general nonparametric form to represent messages and formulate their calculation by numerical integrations for hybrid models. The method requires extensive functional estimations, samplings, and numerical integrations, and therefore is very computational intensive.

Under the framework of a message passing algorithm, first of all, we need to find a general way to represent messages. Essentially, messages are likelihoods or probabilities. In discrete case, messages are represented and manipulated by probability vectors and conditional probability tables (CPTs) which is relatively straightforward. For continuous variables, however, it is more complicated for message representation and manipulation as they may have arbitrary distributions. In this paper, we propose to use the first two moments, mean and variance, of a probability distribution to represent the continuous message regardless of its distribution. This simplification makes message calculation and propagation efficient between continuous variables while keeping the key information of the original distributions. Furthermore, to deal with the possible arbitrary functional relationship between continuous variables, a state estimation method is needed to approximate the distribution of a random variable that has gone through nonlinear transformation. Several weighted sampling algorithms such as particle filtering [1] and Bayesian bootstrapping [2] for nonlinear state estimation were proposed in the literature. However, we prefer to use unscented transformation [14, 15] due to its computational efficiency and accuracy. Unscented transformation uses a deterministic sampling scheme and can provide good estimates of the first two moments for the continuous variable undergone nonlinear transformation. For arbitrary continuous network, this approach we called unscented message passing (UMP) works very well [25]. But in the hybrid model, message propagation between discrete and continuous variables is not straightforward due to their different formats. To deal with this issue, we propose to apply conditioning. First we partition the original hybrid BNs into separate, discrete, and continuous network segments by conditioning on discrete parents of continuous variables [26]. We can then process message passing separately for each network segment before final integration.

One of the benefits of partitioning networks is to ensure that there is at least one efficient inference method applicable to each network segment. In hybrid networks, we assume that a continuous node is not allowed to have any discrete child node. Therefore, the original networks can be partitioned into separate parts by the discrete parents of continuous variables. We call these nodes the interface nodes. Each network segment separated by the interface nodes consists of purely discrete or continuous variables. By conditioning on interface nodes, the variables in different network segments are independent of each other. We then conduct loopy propagation separately in each subnetwork. Finally, messages computed in different segments are integrated through the interface nodes. We then estimate the posterior distribution of every hidden variable given evidence in all network segments.

The algorithm proposed in this paper aims to tackle nonlinear hybrid models. We believe that the proposed combination of known efficient methods and the introduction of interface nodes for hybrid network partition makes the new algorithm a good alternative for inference in nonlinear hybrid models. The remainder of this paper is organized as follows. Section II first reviews Pearl's message passing formulae. We then discuss the message representation and manipulation for continuous variable and how to propagate messages between continuous variables

with nonlinear functional relationship. Section III describes the methods of network partition and message integration by introducing the concept of interface nodes. We show how message passing can be done separately and finally integrated together via the channel of interface nodes. Section IV presents the algorithm of hybrid message passing by conditioning. Several numerical experiments are presented in Section V. Finally, Section VI concludes the research we have done in this paper and suggests some potential future work.

II. MESSAGE PASSING: REPRESENTATION AND PROPAGATION

Pearl's message passing algorithm [24] is the first exact inference algorithm developed originally for polytree discrete BNs. Applying Pearl's algorithm in the network with loops usually provides approximate answers, and this method is called LBP. Recall that in Pearl's message passing algorithm, $\mathbf{e}_X^+$ and $\mathbf{e}_X^-$ are defined as the evidence from the subnetwork "above" a node X and the subnetwork "below" X, respectively. In a polytree, any node X d-separates the set of evidence $\mathbf{e}$ into $\{\mathbf{e}_X^+, \mathbf{e}_X^-\}$. In the algorithm, each node in the network maintains two values called λ value and π value. λ value of a node X, defined as

$$\lambda(X) = P(\mathbf{e}_X^- \mid X) \tag{1}$$

is the likelihood of observations $\mathbf{e}_X^-$ given X. π value of a node X, defined as

$$\pi(X) = P(X \mid \mathbf{e}_X^+) \tag{2}$$

is the conditional probability of X given $\mathbf{e}_X^+$.

The belief of a node X given all evidence is the normalized product of π value and λ value. Each node, after updating its own belief, sends new λ message to its parents and new π message to its children. For a typical node X with m parents $\mathbf{T}(T_1, T_2, \ldots, T_m)$ and n children $\mathbf{Y}(Y_1, Y_2, \ldots, Y_n)$ as illustrated in Fig. 1, the conventional propagation equations of Pearl's message passing algorithm can be expressed as the following [24]:

$$\mathrm{BEL}(X) = \alpha \pi(X) \lambda(X) \tag{3}$$

$$\lambda(X) = \prod_{j=1}^{n} \lambda_{Y_j}(X) \tag{4}$$

$$\pi(X) = \sum_{\mathbf{T}} P(X \mid \mathbf{T}) \prod_{i=1}^{m} \pi_X(T_i) \tag{5}$$

$$\lambda_X(T_i) = \sum_{X} \lambda(X) \sum_{T_k : k \neq i} P(X \mid \mathbf{T}) \prod_{k \neq i} \pi_X(T_k) \tag{6}$$

$$\pi_{Y_j}(X) = \alpha \left[\prod_{k \neq j} \lambda_{Y_k}(X) \right] \pi(X) \tag{7}$$

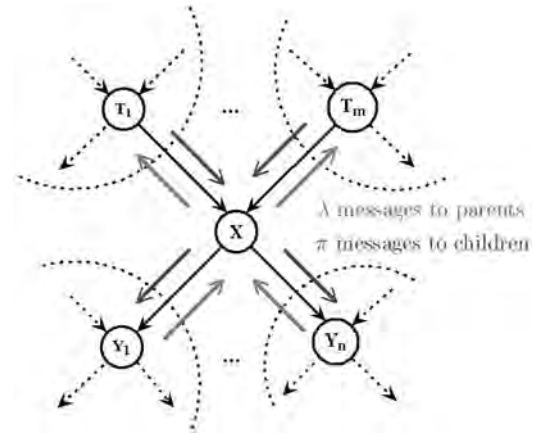

Fig. 1. Typical node X with m parents and n children.

where $\lambda_{Y_j}(X)$ is the λ message node X receives from its child Y_j, $\lambda_X(T_i)$ is the λ message X sends to its parent T_i; $\pi_X(T_i)$ is the π message node X receives from its parent T_i, $\pi_{Y_j}(X)$ is the π message X sends to its child Y_j; and α is a normalizing constant.

When this algorithm is applied to a polytree network, the messages propagated are exact and so are the beliefs of all nodes after receiving all messages. For the network with loops, we can still apply this algorithm as the "loopy propagation" mentioned above. In general, loopy propagation will not provide the exact solutions. But empirical investigations on its performance have reported surprisingly good results.

For discrete variables, messages could be represented by probability vectors, and the conditional probability table of node X given its parent T, $P(X \mid \mathbf{T})$, could be represented by a matrix. Therefore the calculations in the above formulae are the product of vectors and multiplication of vector and matrices, which can be carried out easily. However, for continuous variables, message representation and the corresponding calculations are much more complicated. First, an integral replaces summation in the above equations. Furthermore, since continuous variable could have arbitrary distribution over the continuous space, in general it is very difficult to obtain exact close-form analytical results when combining multiple continuous distributions. In order to make the computations feasible while keeping the key information, we use the first two moments, mean and variance, to represent continuous message regardless of the original distribution. Then, the product of different continuous distributions could be approximated with a Gaussian distribution. Note that for the continuous case, $P(X \mid \mathbf{T})$ is a continuous conditional distribution, and it may involve an arbitrary function between continuous variables. To integrate the product of continuous distributions as shown in (5) and (6), it has to take into account the functional transformation of continuous variables. Fortunately, unscented transformation [14, 15] provides good estimates of mean and variance for the

continuous variables through nonlinear transformation. In our algorithm, unscented transformation plays a key role for computing continuous messages. Specifically, we use it to formulate and compute the π and λ messages since both computations involve the conditional probability distribution in which nonlinear transformation may be required.

A. Unscented Transformation

Proposed in 1996 by Julier and Uhlmann [15], unscented transformation is a deterministic sampling method to estimate mean and variance of continuous random variable that has undergone nonlinear transformation. Consider the following problem: a continuous random variable $\mathbf{x}$ with mean $\bar{\mathbf{x}}$ and covariance matrix $\mathbf{P_x}$ undergoes an arbitrary nonlinear transformation, written as $\mathbf{y} = g(\mathbf{x})$; the question is how to compute the mean and covariance of $\mathbf{y}$?

From probability theory, we have

$$p(\mathbf{y}) = \int_{\mathbf{x}} p(\mathbf{y} \mid \mathbf{x}) p(\mathbf{x}) dx.$$

However, in general the above integral may be difficult to compute analytically and may not always have a close-form solution. Therefore, instead of finding the distribution, we retreat to seek for its mean and covariance. Based on the principle that it is easier to approximate a probability distribution than an arbitrary nonlinear function, unscented transformation uses a minimal set of deterministically chosen sample points called sigma points to capture the true mean and covariance of the prior distribution. Those sigma points are propagated through the original functional transformation individually. According to its formulae, posterior mean and covariance calculated from these propagated sigma points are accurate to the 2nd order for any nonlinearity. In the special case when the transformation function is linear, the posterior mean and variance are exact.

The original unscented transformation encounters difficulties with high-dimensional variables, so the scaled unscented transformation was developed soon afterward [14]. The scaled unscented transformation is a generalization of the original unscented transformation. We will use the two terms interchangeably, but both mean scaled unscented transformation in the remainder of this paper.

Now let us describe the formulae of unscented transformation. Assume $\mathbf{x}$ is L-dimensional multivariate random variable. First, a set of $2L + 1$ sigma points are specified by the following formulae:

$$\lambda = \alpha^2(L+\kappa) - L$$
$$\mathcal{X} = \begin{cases} \mathcal{X}_0 = \bar{\mathbf{x}} & i = 0 \\ \mathcal{X}_i = \bar{\mathbf{x}} + \left(\sqrt{(L+\lambda)\mathbf{P_x}}\right)_i & i = 1,\ldots,L \\ \mathcal{X}_i = \bar{\mathbf{x}} - \left(\sqrt{(L+\lambda)\mathbf{P_x}}\right)_i & i = L+1,\ldots,2L \end{cases} \tag{8}$$

and the associated weights for these $2L + 1$ sigma points are

$$\begin{aligned} w_0^{(m)} &= \frac{\lambda}{L+\lambda} \qquad i = 0 \\ w_0^{(c)} &= \frac{\lambda}{L+\lambda} + (1-\alpha^2+\beta) \qquad i = 0 \\ w_0^{(m)} &= w_0^{(c)} = \frac{1}{2(L+\lambda)} \qquad i = 1,\ldots,2L \end{aligned} \tag{9}$$

where α, β, κ are scaling parameters and the superscripts "(m)," "(c)" indicate the weights for computing posterior mean and covariance, respectively. The values of scaling parameters could be chosen by $0 \le \alpha \le 1$, $\beta \ge 0$, and $\kappa \ge 0$. It has been shown empirically that the specific values chosen for the parameters are not critical because unscented transformation is not sensitive to those parameters. We choose $\alpha = 0.8$, $\beta = 2$ (optimal for Gaussian prior [14]), and $\kappa = 0$ in all of our experiments.

After the sigma points are selected, they are propagated through the functional transformation:

$$\mathcal{Y}_i = \mathbf{g}(\mathcal{X}_i) \qquad i = 0,\ldots,2L. \tag{10}$$

Finally, the posterior mean and covariance are estimated by combining the propagated sigma points as follows:

$$\bar{\mathbf{y}} \approx \sum_{i=0}^{2L} w_i^{(m)} \mathcal{Y}_i \tag{11}$$

$$\mathbf{P_y} \approx \sum_{i=0}^{2L} w_i^{(c)} (\mathcal{Y}_i - \bar{\mathbf{y}})(\mathcal{Y}_i - \bar{\mathbf{y}})^{\mathbf{T}} \tag{12}$$

$$\mathbf{P_{xy}} \approx \sum_{i=0}^{2L} w_i^{(c)} (\mathcal{X}_i - \bar{\mathbf{x}})(\mathcal{Y}_i - \bar{\mathbf{y}})^{\mathbf{T}}. \tag{13}$$

In short, we denote the unscented transformation for X undergoing a functional transformation $Y = f(X)$ as the following:

$$(Y.\mathrm{mu}, Y.\mathrm{cov}) = UT\left(X \xrightarrow{f(X)} Y\right). \tag{14}$$

We demonstrate the unscented transformation by a simple two-dimension Gaussian example. Let $\mathbf{x} = [x_1 \;\; x_2]$ with mean and covariance matrix given as

$$\bar{\mathbf{x}} = \begin{bmatrix} 3 \\ 1 \end{bmatrix}, \qquad \mathbf{P_x} = \begin{bmatrix} 1 & -1 \\ -1 & 2 \end{bmatrix}.$$

In order to show the robustness of unscented transformation, we choose a set of functions with severe nonlinearity shown below:

$$y_1 = \log(x_1^2)\cos(x_2), \qquad y_2 = \sqrt{\exp(x_2)}\sin(x_1 x_2).$$

The true posterior statistics are approximated very closely by brute force Monte Carlo simulation

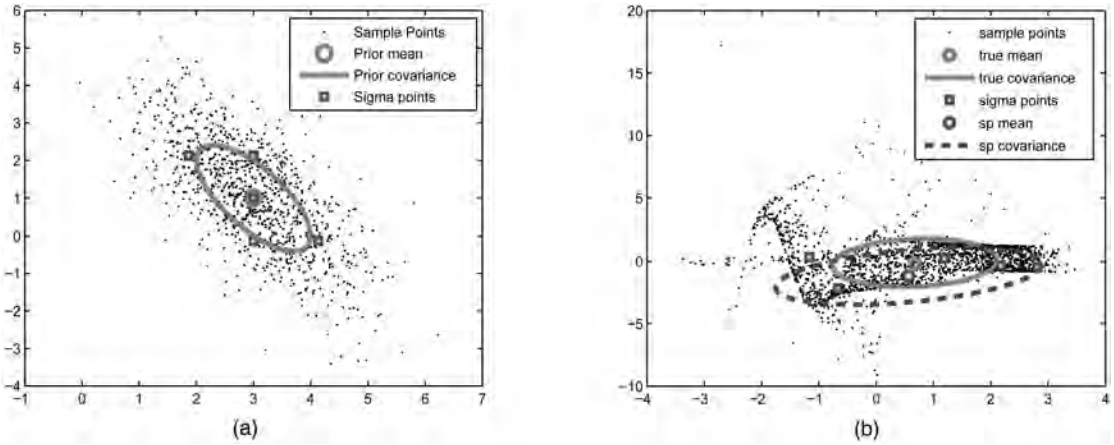

Fig. 2. Demonstration of unscented transformation. (a) Prior distribution. (b) After nonlinear transformation.

using 100,000 sample points drawn from the prior distribution and then propagated through the nonlinear mapping. We compare them with the estimates calculated by unscented transformation using only 5 sigma points. Fig. 2 shows that the mean calculated by transformed sigma points is very close to the true mean and that the posterior covariance seems consistent and efficient because the sigma-point covariance ellipse is larger but still tight around the true posterior covariance ellipse.

B. Unscented Message Passing

Now let us take a closer look at Pearl's general message propagation formulae shown in (3)–(7). In recursive Bayesian inference, π message represents prior information and λ message represents evidential support in the form of a likelihood function. Equations (3), (4), and (7) are essentially the combination of different messages by multiplication. They are similar to the data fusion concept where estimates received from multiple sources are combined.

Under the assumption of Gaussian distribution, the fusion formula is relatively straightforward [3]. Specifically, (3), (4), and (7) can be rewritten in terms of the first two moments of the probability distributions as the following:

$$\mathrm{BEL}(X)\begin{cases}\mathrm{cov} = \left(\dfrac{1}{\pi(X).\mathrm{cov}} + \dfrac{1}{\lambda(X).\mathrm{cov}}\right)^{-1} \\ \mathrm{mu} = \mathrm{cov}\left[\dfrac{\pi(X).\mathrm{mu}}{\pi(X).\mathrm{cov}} + \dfrac{\lambda(X).\mathrm{mu}}{\lambda(X).\mathrm{cov}}\right]\end{cases} \tag{15}$$

$$\lambda(X)\begin{cases}\mathrm{cov} = \left(\displaystyle\sum_{j=1}^{n}\dfrac{1}{\lambda_{Y_j}(X).\mathrm{cov}}\right)^{-1} \\ \mathrm{mu} = \mathrm{cov}\left[\displaystyle\sum_{j=1}^{n}\dfrac{\lambda_{Y_j}(X).\mathrm{mu}}{\lambda_{Y_j}(X).\mathrm{cov}}\right]\end{cases} \tag{16}$$

$$\pi_{Y_j}(X)\begin{cases}\mathrm{cov} = \left(\dfrac{1}{\pi(X).\mathrm{cov}} + \displaystyle\sum_{k\neq j}\dfrac{1}{\lambda_{Y_k}(X).\mathrm{cov}}\right)^{-1} \\ \mathrm{mu} = \mathrm{cov}\left[\dfrac{\pi(X).\mathrm{mu}}{\pi(X).\mathrm{cov}} + \displaystyle\sum_{k\neq j}\dfrac{\lambda_{Y_k}(X).\mathrm{mu}}{\lambda_{Y_k}(X).\mathrm{cov}}\right]\end{cases} \tag{17}$$

where mu, cov stand for corresponding mean and covariance, respectively.

Equation (5) computes the π value for node X. Analytically, this is equivalent to treating X as a functional transformation of $\mathbf{T}$ and the function is the one defined in CPD of X denoted as $h(X)$. Technically, we take $\mathbf{T}$ as a multivariate random variable with a mean vector and a covariance matrix; then by using unscented transformation, we obtain an estimate of mean and variance of X to serve as the π value for node X. In (5), $\pi_X(T_i)$ is the π messages sending to X from its parent T_i, which is also represented by mean and covariance. By combining all the incoming $\pi_X(T_i)$ messages, we can estimate the mean vector and covariance matrix of $\mathbf{T}$. Obviously, the simplest way is to view all parents as independent variables; then combine their means into a mean vector, and place their variances at the diagonal positions to form a diagonal covariance matrix.[2] With that, we can compute the π value of node X by

$$(\pi(X).\mathrm{mu}, \pi(X).\mathrm{cov}) = UT\left(\mathbf{T} \xrightarrow{h(X)} X\right). \tag{18}$$

Similarly but a bit more complicated, (6) computes the λ message sending to its parent (T_i) from node X. Note here that we integrate out X and all of its parents except the one (T_i) we are sending λ message to. Theoretically, this is equivalent to regarding T_i as the functional transformation of X and $\mathbf{T}\backslash T_i$. It

[2]This is actually how the original loopy algorithm works and why it is not exact. To improve the algorithm, we can estimate the correlations between all parents and include them in the covariance matrix of $\mathbf{T}$.

is necessary to mention that the function used for transformation is the inverse function of the original one specified in $P(X \mid \mathbf{T})$ with T_i as the independent variable. We denote this inverse function as $v(X, \mathbf{T}\backslash T_i)$. Note that in practical problems, the original function may not be invertible, or its inverse function may not be unique. In such a case, we need additional steps to apply the method. In this paper, we assume the inverse function is unique and always available. To compute the message, we first augment X with $\mathbf{T}\backslash T_i$ to obtain a new multivariate random variable called $\mathbf{TX}$; then the mean vector and covariance matrix of $\mathbf{TX}$ are estimated by combining $\lambda(X)$ and $\pi_X(T_k)(k \neq i)$. After applying unscented transformation to $\mathbf{TX}$ with the new inverse function $v(X, \mathbf{T}\backslash T_i)$, we obtain an estimate of the mean and variance for T_i serving as the $\lambda_X(T_i)$ message as below:

$$(\lambda_X(T_i).\text{mu}, \lambda_X(T_i).\text{cov}) = UT\left(\mathbf{TX}^{v(X,\mathbf{T}\backslash T_i)} \longrightarrow T_i\right). \quad (19)$$

With (15)–(19), we can now compute all messages for continuous variables. As one may notice, unscented transformation plays a key role here. This is why we call it UMP for continuous BNs.

So far, we have summarized message representation and propagation for discrete and continuous variables, respectively. However, for the hybrid model, we have to deal with the messages passing between both types of variables. Since they are in different formats, messages cannot be integrated directly. As mentioned in Section I, our approach is to partition the original network before propagating messages between them.

III. NETWORK PARTITION AND MESSAGE INTEGRATION FOR HYBRID MODEL

First of all, as mentioned earlier, we assume that a discrete node can only have discrete parents in the hybrid models, which implies continuous variable cannot have any discrete child node.

DEFINITION 1 In a hybrid BN, a discrete variable is called a discrete parent if and only if it has at least one continuous child node.

It is well known that BN has an important property that every node is independent of its nondescendant nodes given its parents. Therefore the following theorem follows.

THEOREM 1 *All discrete parents in the hybrid BN model can partition the network into independent network segments, each having either purely discrete or purely continuous variables. We call the set of all discrete parents in the hybrid network the interface nodes. In other words, the interface nodes "d-separate" the network into different network segments.*

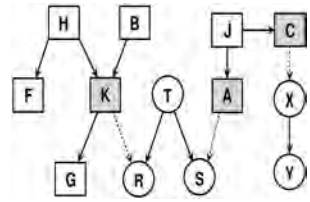

Fig. 3. Demonstration of interface nodes and network partition.

It is obvious that the variables in different segments of the network are independent of each other given the interface nodes. An example is shown in Fig. 3 where a 13-node hybrid model is presented. Following the convention, we use a square or rectangle to depict the discrete variable and a circle or ellipse to depict the continuous variable. As can be seen, K, A, and C are the interface nodes in this example. By representing the arcs between discrete parents and their continuous children as dot lines, four independent network segments are formulated—two discrete parts (H, B, F, K, G and J, A, C) and two continuous parts (T, R, S and X, Y).

After partitioning the network with the interface nodes, we choose the most appropriate inference algorithm for each network segment. In fact, we can also combine some segments together if the same algorithm works for all of them. The purpose of introducing the interface nodes is to facilitate the network partition so that at least one algorithm could be applicable to each segment. In general, separate message passing in either discrete or continuous network segment is always doable. Typically, the continuous network segment with nonlinear and/or non-Gaussian CPDs is the most difficult one to deal with. In such case, we apply UMP presented in Section IIB for approximate solutions.

Finally, we need to summarize the prior and evidence information for each network segment and encode it as messages to be passed between network segments through the interface nodes. This is similar to general message passing but requires message integrations between different network segments.

A. Message Integration for Hybrid Model

For a hybrid model, without loss of generality, let us assume that the network is partitioned into two parts denoted as $\mathcal{D}$ and $\mathcal{C}$. Part $\mathcal{D}$ is a discrete network and it is solvable by appropriate algorithms such as junction tree or discrete loopy propagation. Part $\mathcal{C}$ is an arbitrary continuous network. Let us denote the observable evidence in part $\mathcal{D}$ as E_d, and the evidence from $\mathcal{C}$ as E_c. Therefore the entire evidence set $\mathbf{E}$ consists of E_d and E_c. As mentioned before, given interface nodes, variables from the two network segments are conditional independent of each other. The evidence from part $\mathcal{D}$ affects the posterior

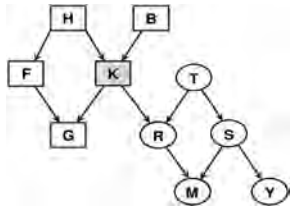

Fig. 4. Synthetic hybrid Bayesian networks-1.

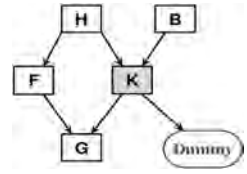

Fig. 5. Transformed model with dummy node.

probability of hidden nodes in part $\mathcal{C}$ and vice versa only through the channel of the interface nodes.

We therefore summarize the prior and evidence information of each network segment and encode them as either π or λ value at the interface nodes. Assuming that the set of interface nodes between two network segments is $\mathbf{I}$, then the two messages are: $\lambda(\mathbf{I}) = P(E_c \mid \mathbf{I})$ and $\pi(\mathbf{I}) = P(\mathbf{I} \mid E_d)$. These values are to be passed between network segments to facilitate information integration. As in Pearl's algorithm, this approach can be easily integrated with the UMP-BN loopy algorithm mentioned above in a unified manner.

We use the following concrete example to illustrate how to integrate messages from different network segments. As can be seen in Fig. 4, synthetic hybrid model-1 has K as the interface node dividing the network into a discrete part consisting of H, B, F, K, G and a continuous part consisting of T, R, S, M, Y. For the purpose of illustration, let us assume all discrete nodes are binary and all continuous nodes are scalar Gaussian variables.

Suppose the leaf nodes G, M, Y are observable evidence. We first focus on the continuous segment. In this step, we compute the λ message sending to the interface node K from continuous evidence. And conditioning on each possible state of K, we estimate the posterior distributions for all hidden continuous variables given continuous evidence. Under Gaussian assumption, these posterior distributions are represented by means and variances and they are intermediate results that will be combined after we obtain the a posterior probability distribution of the interface node K given all evidence. Probabilities of all possible states of K are served as the mixing weights, similar to computing the mean and variance of a Gaussian mixture.

Given K, it is straightforward to compute the likelihood of continuous evidence $M = m$, $Y = y$ because we can easily estimate the conditional probability distribution of evidence node given interface nodes and other observations. For example, let

$$P(M = m, Y = y \mid K = 1) = a$$

$$P(M = m, Y = y \mid K = 2) = b.$$

Then to incorporate the evidence likelihood is equivalent to adding a binary discrete dummy node as the child of the interface node K with the conditional probability table shown as the following:

	Dummy	
K	1	2
1	αa	1-αa
2	αb	1-αb

where α is a normalizing constant.

By setting "Dummy" to be observed as state 1, the entire continuous segment could be replaced by the node Dummy. Then the original hybrid BN can be transformed into a purely discrete model shown in Fig. 5 in which Dummy integrates all of the continuous evidence information.

The second step is to compute the posterior distributions for all hidden discrete nodes given $G = g$, Dummy = 1. We have several algorithms to choose for inference depending on the complexity of the transformed model. In general, we can always apply discrete loopy propagation algorithm to obtain approximate results regardless of network topology. Note that the posterior distributions of the discrete nodes have taken into account all evidence including the ones from continuous segment via the Dummy node. However, we need to send the updated information back to the continuous subnetwork via the set of interface nodes. This is done by computing the joint posterior probability distribution of the interface nodes denoted as $P(\mathbf{I} \mid \mathbf{E})$. Essentially, it is the π messages to be sent to the continuous network segment.

With the messages encoded in the interface nodes, the last step is to go back to the continuous segment to compute the a posterior probability distributions for all hidden continuous variables. Recall that in the first step, for any hidden continuous variable X, we already have $P(X \mid \mathbf{I}, E_c)$ computed and saved. The following derivation shows how to compute $P(X \mid \mathbf{E})$:

$$\begin{aligned} P(X \mid \mathbf{E}) &= P(X \mid E_c, E_d) \\ &= \sum_{\mathbf{I}} P(X, \mathbf{I} \mid E_c, E_d) \\ &= \sum_{\mathbf{I}} P(X \mid \mathbf{I}, E_c, E_d) P(\mathbf{I} \mid E_c, E_d) \\ &= \sum_{\mathbf{I}} P(X \mid \mathbf{I}, E_c) P(\mathbf{I} \mid \mathbf{E}). \end{aligned} \tag{20}$$

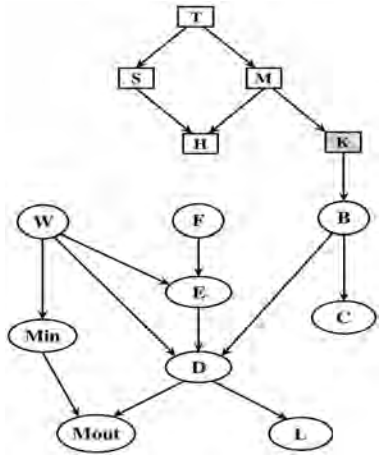

Fig. 6. GHM-2.

The fourth equality is due to the fact that the set of interface node d-separate the node X with E_d.

Assuming given an instantiation of the set of interface nodes $\mathbf{I} = i$, $P(X \mid \mathbf{I} = i, E_c)$ is a Gaussian distribution with mean $\bar{x}_i$ and variance σ_i^2. Then (20) is equivalent to computing the probability density function of a Gaussian mixture with $P(\mathbf{I} = i \mid \mathbf{E})$ as the weighting factors. Denoting $P(\mathbf{I} = i \mid \mathbf{E})$ as p_i, the mean $\bar{x}$ and the variance σ_x^2 of $P(X \mid \mathbf{E})$ can be computed as the following [3, p. 56]:

$$\bar{x} = \sum_i p_i \bar{x}_i \tag{21}$$

$$\sigma_x^2 = \sum_i p_i \sigma_i^2 + \sum_i p_i \bar{x}_i^2 - \bar{x}^2. \tag{22}$$

Through the above three steps, we successfully integrate messages from different subnetworks to obtain the approximate posterior marginal distribution for both continuous and discrete hidden variables given all evidence. There are two approximations in the algorithm. One is from loopy propagation method itself. Another one is that we approximate continuous variable as Gaussian distributed as we only use the first two moments to represent continuous messages. However, it provides promising performance as seen in the numerical experiment results.

IV. HYBRID MESSAGE PASSING ALGORITHM

We have presented separate message passing in either discrete or continuous network segment and message integration in hybrid model via interface nodes. In this section, we summarize the general algorithm of message passing for hybrid BNs as shown in Table I.

In order to incorporate evidence information, we allow a node to send a λ message to itself. For a discrete network, we initialize the messages by letting all evidence nodes send to themselves a vector of a "1" for observed state and 0s for other states. All other messages are initialized as vectors of 1s. For continuous network, a message is represented by mean and variance. We initialize the messages for all continuous evidence nodes, sending themselves as the one with the mean equal to the observed value and the variance equal to zero. All other messages in continuous network are initialized as uniform, specifically, zero-mean and infinity variance (the so-called "diffusion prior"). Then in each iteration, every node computes its own belief and outgoing messages based on the incoming messages from its neighbors. We assess the convergence by checking if any belief change is less than a prespecified threshold (for example, 10^{-4}). We use parallel updating for each node until the messages are converged.

TABLE I
Hybrid Message Passing Algorithm for General Mixed BN

Algorithm: Hybrid Message Passing for General Mixed BN (HMP-BN).

Input: General hybrid BN given a set of evidence.

Output: Posterior marginal distributions of all hidden nodes.

1. Determine the interface nodes and partition the network into independent segments with interface nodes. Choose the appropriate inference algorithm for each network segment.
2. Continuous network segment: compute the λ message sending to the interface nodes and the intermediate posterior distribution of the hidden continuous variables given the interface nodes and the local evidence.
3. Transform the original network into an equivalent discrete model with a dummy node added as a child of the interface nodes. This dummy discrete node carries the λ message from continuous evidence to the interface nodes.
4. Compute the posterior distribution for every hidden discrete variable using the transformed discrete model. The joint posterior probability table of the interface nodes is saved as the π message to be sent back to the continuous network segment.
5. Compute the posterior distribution for every hidden continuous variable given all evidence by integrating the π message using (20).

V. NUMERICAL EVALUATION

A. Experiment Method

We use two synthetic hybrid models for experiments. One is shown in Fig. 4 as mentioned in Section IIIA called GHM-1. GHM-1 has one loop in each network segment, respectively, (partitioned by the interface node K). Another experiment model is shown in Fig. 6 called GHM-2. GHM-2 has multiple loops in the continuous segment.

For GHM-1, we assume that the leaf nodes G, M, Y are observable evidence. We model its continuous segment as a linear Gaussian network given the interface node K. Therefore the original network is a

CLG so that the exact inference algorithm (junction tree) can be used to provide the true answer as a golden standard for performance comparison. The CPTs and CPDs for nodes in GHM-1 are randomly specified.

Note that our algorithm can handle general arbitrary hybrid model, not just CLG. GHM-2 is designed specifically to test the algorithm under the situation where nonlinear CPDs are involved in the model. The structure of the continuous segment in GHM-2 is borrowed from [17] in which the author proposed junction tree algorithm for CLG. The discrete nodes in the GHM-2 are binary, and we randomly specify the CPTs for them similar to the one in GHM-1. But the CPDs for the continuous nodes are deliberately specified using severe nonlinear functions shown below to test the robustness of the algorithm:

$$\begin{aligned}
\mathbf{F} &\sim \mathcal{N}(-10,3)\\
\mathbf{W} &\sim \mathcal{N}(100,10)\\
\mathbf{B} \mid \mathbf{K} = \mathbf{1} &\sim \mathcal{N}(50,5)\\
\mathbf{B} \mid \mathbf{K} = \mathbf{2} &\sim \mathcal{N}(60,5)\\
\mathbf{E} &\sim \mathcal{N}(W+2F,1)\\
\mathbf{C} &\sim \mathcal{N}(e^{\sqrt[3]{B}},3)\\
\mathbf{D} &\sim \mathcal{N}(\sqrt{W}\times\log(E)-B,5)\\
\mathbf{Min} &\sim \mathcal{N}(\sqrt{W}+6,3)\\
\mathbf{Mout} &\sim \mathcal{N}(0.5\times D\times \mathrm{Min},5)\\
\mathbf{L} &\sim \mathcal{N}(-5\times D,5).
\end{aligned}$$

We assume that the evidence set in the GHM-2 is $\{H,C,\mathrm{Mout},L\}$. Since no exact algorithm is available for such model, for comparison purposes, we use the brute force sampling method, likelihood weighting, to obtain an approximate true solution with a large number of samples (20 million samples).

In our experiments, we first randomly sample the network and clamp the evidence nodes by their sampled value. Then we run HMP-BN to compute the posterior distributions for the hidden nodes. It is important to mention that in both discrete and continuous network segments, we implement HMP-BN using loopy algorithms to make it general, although junction tree could be used in network segment whenever it is applicable. In addition, we run LW using as many samples as it can generate within roughly the same amount of time HMP-BN consumes. There are 10 random runs for GHM-1 and 5 random runs for GHM-2. We compare the average Kullback-Leibler (KL) divergences of the posterior distributions obtained by different algorithms.

Given unlikely evidence, it is well known that the sampling methods converge very slowly even with a large sample size. We use GHM-1 to test the robustness of our algorithm in this case because junction tree can provide the ground true for GHM-1 regardless of the evidence likelihood. We generate 10 random cases with evidence likelihood between $10^{-5} \sim 10^{-15}$ and run both HMP-BN and LW to compare the performances.

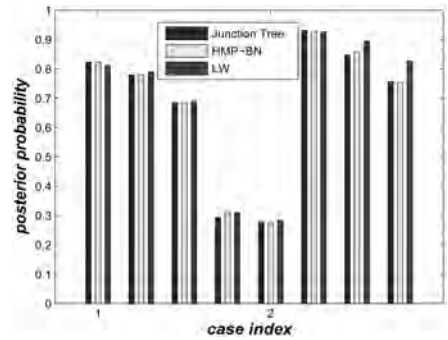

Fig. 7. Posterior probability of hidden discrete variables in two typical runs.

B. Experiment Results

For model GHM-1, there are 4 hidden discrete nodes and 3 hidden continuous nodes. Fig. 7 illustrates the posterior probabilities of hidden discrete nodes computed by junction tree, HMP-BN, and LW in two typical runs. Since GHM-1 is a simple model and we did not use unlikely evidence, both HMP-BN and LW perform well.

For continuous variables in GHM-1, Fig. 8 shows the performance comparisons in means and variances of the posterior distributions for the hidden continuous nodes in all of the 10 runs. The normalized error is defined as the ratio of the absolute error over the corresponding true value. From the figure, it is evident that HMP-BN provides accurate estimates of means, while the estimated variances deviate from the true somewhat but HMP-BN is still better than LW in most cases.

We then demonstrate the robustness of HMP-BN by testing its performance given unlikely evidence shown in Fig. 9. In this experiment, 10 random sets of evidence are chosen with likelihood between 10^{-5} and 10^{-15}. As can be seen, HMP-BN performs significantly better than LW in this case. The average KL divergences are consistently small with the maximum value less than 0.05. This is not surprising because LW uses the prior to generate samples so that it hardly hits the area close to the observations.

We summarize the performance results with GHM-1 in Table II. Note that given unlikely evidence, the average KL divergence by HMP-BN is more than one order of magnitude better than LW.

In GHM-2, due to the nonlinear nature of the model, no exact method exists to provide the benchmark. We use LW with 20 million samples to obtain an approximation of the true value. We implemented five simulation runs with randomly

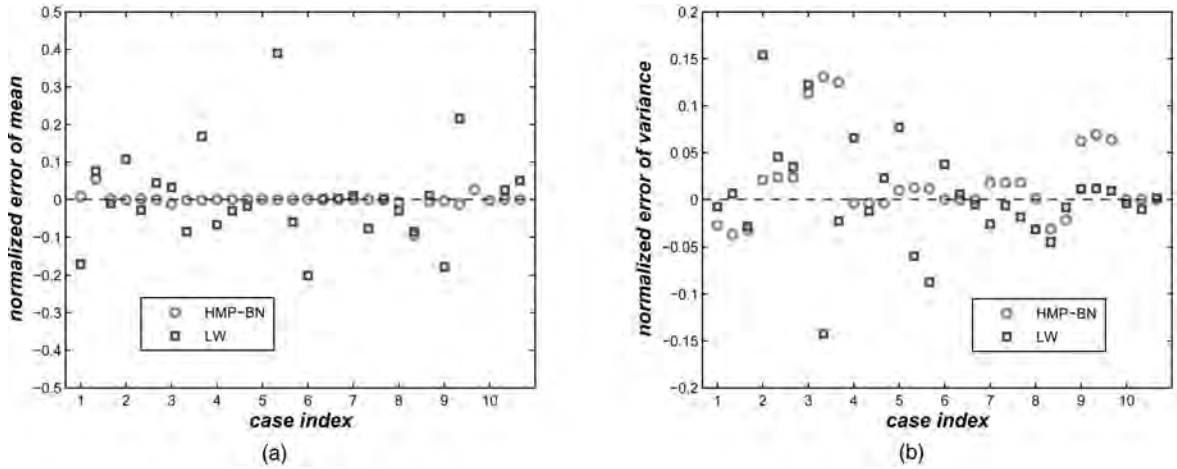

Fig. 8. GHM-1 Performance comparison for 10 random runs (ground true is provided by junction tree). (a) Mean comparison. (b) Variance comparison.

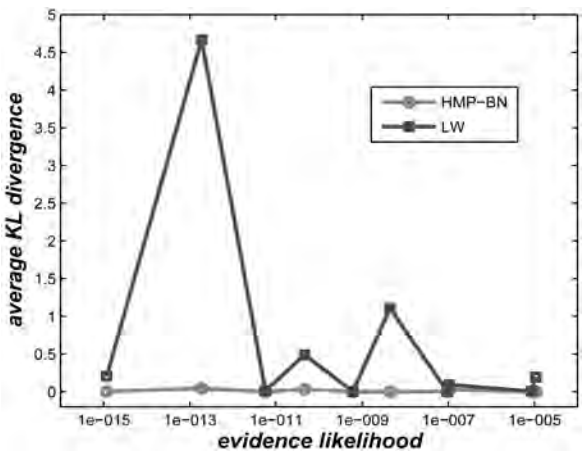

Fig. 9. GHM-1: Performance comparison given unlikely evidence.

TABLE II
Average KL-Divergence Comparison in Testing GHM-1

Average KL divergence	Normal Evidence $> 10^{-5}$	Unlikely Evidence 10^{-5}–10^{-15}
HMP-BN	0.0011	0.0108
LW	0.0052	0.67

TABLE III
Average KL-Divergence Comparison in Testing GHM-2

	Average KL Divergence
HMP-BN	0.0056
LW	0.0639

sampled evidence. In this experiment, we adopt our newly developed algorithm UMP-BN for inference in continuous network segment [25]. Fig. 10 shows the performance comparison in means and variances of the posterior distribution for the hidden continuous variables. Also, Table III summarizes the average KL divergences in testing GHM-2. From the data, we see that HMP-BN combining with UMP-BN applied in the continuous subnetwork produces very good results. In this nonlinear model with the normal evidence, the new algorithm performs much better than LW despite its advantages of being a model-free algorithm. However, since there is only one interface node in these models, implementing HMP-BN is relatively simple.

C. Complexity of HMP-BN

In general, when there are multiple interface nodes, HMP-BN computes the posterior distributions of hidden continuous variables given continuous evidence, conditioned on every combination of instantiations of all interface nodes. So the complexity of the algorithm is highly dependent on the size of interface nodes. To assess the complexity of HMP-BN, we conducted a random experiment using network structure borrowed from the ALARM model [4] as shown in Fig. 11 in which there are 37 nodes. We randomly selected each node to be discrete or continuous with only a requirement that continuous variable cannot have any discrete child node. In this experiment, the average number of interface nodes was about 12. HMP-BN still provided good estimates of the posterior distributions but it took a much longer time than the one with only one interface node. If we have n interface nodes $K_1, K_2, \ldots, K_n$ with number of states $n_1, n_2, \ldots, n_k$, respectively, the computational complexity of HMP-BN is proportional to $\mathcal{O}(n_1 \times n_2 \times n_3 \cdots \times n_k)$. This implies that our algorithm is not scalable for a large number of interface nodes. However, our goal is not to propose an algorithm for all models (NP-hard in general) and we suspect that it is rare to have a large number of interface nodes in most practical models. Even with the considerable size of interface nodes, HMP-BN provides good results within a reasonable time while the stochastic sampling

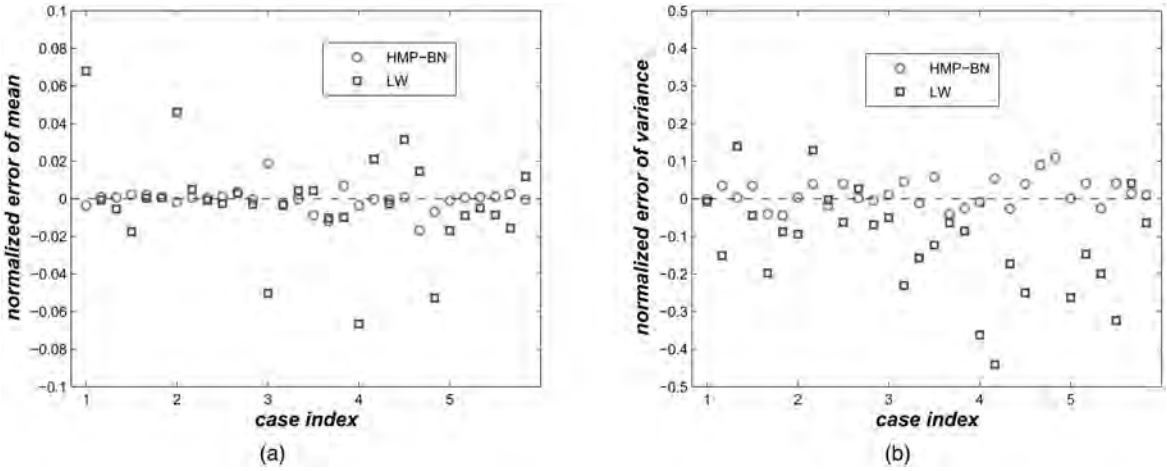

Fig. 10. GHM-2: Performance comparison for 5 random runs (the reference base is provided by LW with 20 millions samples). (a) Mean comparison. (b) Variance comparison.

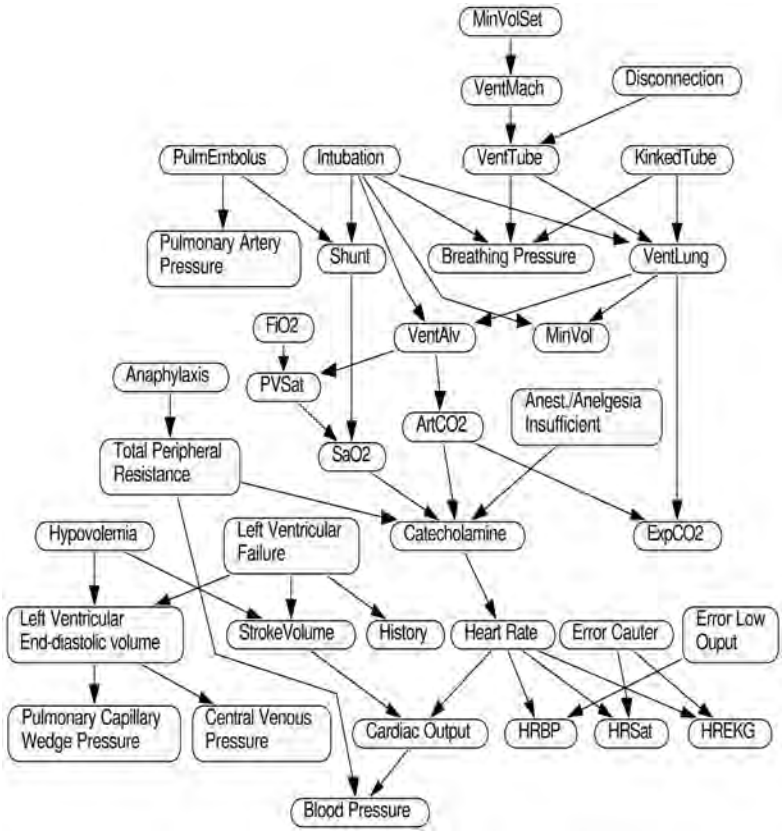

Fig. 11. ALARM: network constructed by medical expert for monitoring patients in intensive care.

methods can perform very poorly using the same amount of time. In addition, there are several ways to reduce the computational burden such as assuming that some interface nodes with small correlations are independent of each other. Nevertheless, this is beyond the scope of the paper and could be an interesting topic for future research.

VI. CONCLUSION

In this paper, we develop a hybrid propagation algorithm for general BNs with mixed discrete and continuous variables. In the algorithm, we first partition the network into discrete and continuous segments by introducing the interface nodes. We then apply message passing for each network segment and encode the updated information as messages to be exchanged between segments through the set of interface nodes. Finally we integrate the separate messages from different network segments and compute the a posterior distributions for all hidden nodes. The preliminary simulation results show that the algorithm works well for hybrid BN models.

The main contribution of this paper is to provide a general framework for inference in hybrid model. Based on the principle of decomposition and conditioning, we introduce the set of interface nodes to partition the network. Therefore it is possible to apply exact inference algorithms such as junction tree to some applicable network segments which enables the integration of different efficient algorithms from multiple subnetworks. For complicated network segment such as the one with nonlinear and/or non-Gaussian variables, we provide options to use a loopy-type message passing algorithm.

Although the bottleneck of our algorithm is the size of interface nodes, we believe that HMP-BN is a good alternative for nonlinear and/or non-Gaussian hybrid models since no efficient algorithm exists for this case (as far as we know from the literature), especially given unlikely evidence. We are currently exploring another idea of propagating messages directly between different types of nodes without network partition or interface nodes. However, it is beyond the scope of the current paper.

Note that the focus of this paper is on developing a unified message passing algorithm for general hybrid networks. While the algorithm works well to estimate the means and variances for the hidden continuous variables, the true posterior distributions may have multiple modes. In practice, it might be more important to know where the probability mass is than just knowing mean and variance. One idea for future research is to utilize the messages computed in HMP-BN to obtain a good importance function and apply importance sampling to estimate the probability distributions. Another future research direction is to extend the hybrid algorithm to the general BN models without restriction of node ordering, such as to allow continuous parents for discrete variables. If successful, it would be a significant step forward.

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Analytical and Computational Evaluation of Scalable Distributed Fusion Algorithms

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The theoretical fundamentals of distributed information fusion have been developed over the past two decades and are now fairly well established. However, practical applications of these theoretical results to dynamic sensor networks have remained a challenge. There has been a great deal of work in developing distributed fusion algorithms applicable to a network centric architecture. In general, in a distributed system such as ad hoc sensor networks, the communication architecture is not fixed. In those cases, the distributed fusion approaches based on pedigree information may not scale because of limited communication bandwidth. In this paper, we focus on scalable fusion algorithms and conduct analytical performance evaluation to compare their performance. The goal is to understand the performance of these algorithms under different operating conditions. Specifically, we evaluate the performance of channel filter fusion, naïve fusion, Chernoff fusion, Shannon fusion, and Bhattacharyya fusion algorithms. We also compare their performance to "optimal" centralized fusion under a specific communication pattern. The results show that the channel filter fusion, representing a first order approximation to the information graph fusion, is the only "consistent" fusion algorithm.

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I. INTRODUCTION

A distributed data fusion system consists of a network of sensors and processors that may be colocated with the sensors. Sensors generate data by observing the environment. Processors process local sensor data and fuse data from other sensors or processors. The performance of a distributed fusion system over a network depends on three factors: the network architecture, the reliability of communication links within the network, and applicable fusion algorithms. Even though the network architecture may be fixed and known, adaptive communication strategies and possible communication link failures will result in a dynamically changing communication structure among the fusion nodes. Thus, a distributed fusion algorithm is not really practical unless it can handle a dynamic communication structure.

There has been a great deal of work in developing distributed fusion algorithms applicable to a network centric architecture [1–5]. However, most of these algorithms have been designed for fixed communication structures and may not be practical for distributed systems such as ad hoc sensor networks where the communication architecture changes dynamically [6]. In particular, the distributed fusion algorithm based on the information graph approach [7] was developed to optimally combine information from multiple nodes by maintaining information pedigree and using it to avoid any double counting of information. However, when the communication structure changes in real time, this algorithm may not scale because of its requirements to carry long pedigree information for decorrelation.

In this paper, we focus on several scalable fusion algorithms and analytically compare their performance through steady-state estimate error prediction. To demonstrate our performance analysis approach, we use a nominal three-node fusion processing scenario with cyclic communications as shown in Fig. 1. We conduct extensive simulations to validate the theoretical predictions. We have chosen this network structure because of its complexity due to multiple paths for information propagation, and the availability of the optimal analytical solution that can be derived and used as a performance baseline.

Specifically, we consider the fusion algorithms listed below and compare their performance against the optimal information fusion solution.

Channel filter
Naïve fusion
Chernoff fusion
Shannon fusion
Bhattacharyya fusion

Our goal is to investigate how these different fusion algorithms perform for a specific scenario under limited communication bandwidth. This is

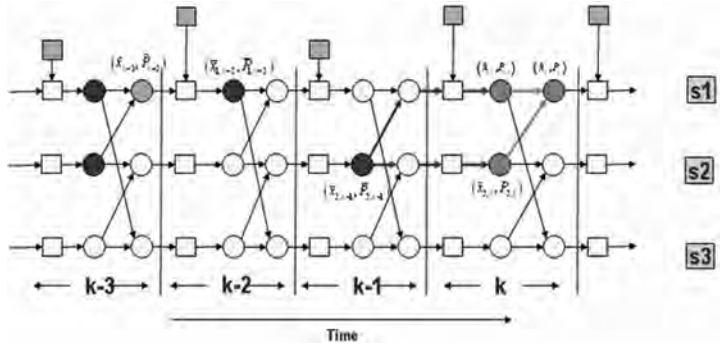

Fig. 1. Three sensor cyclic communication scenario.

part of a wider objective to understand the system trades involved in a general decentralized ad hoc sensor network. The rest of this paper is organized as follows. Section II briefly describes the set of scalable distributed fusion algorithms to be considered in this paper. Section III derives the analytical fusion performance evaluation in terms of steady-state mean square error. Section IV summarizes the technical findings of the study, and Section V presents some future research directions.

II. SCALABLE FUSION ALGORITHMS

The theoretic fundamentals of distributed information fusion are well documented and have been studied in depth [7–11]. It is noted, however, that practical applications of these theoretical results to nondeterministic information flow have remained a challenge. The main difficulty is the need to identify and remove common information from the data sets to be fused, while minimizing the amount of data exchanged between agents.

The basic fusion process, as described in [7], follows from set theory, where the combination of n event probabilities $\Phi(\cdot \mid I_i)$ given the information I_i can be represented as

$$\Phi\left(\cdot \,\middle|\, \bigcup_{i=1}^{n} I_i\right) = \frac{1}{C}\prod_{i=1}^{n} S_i^{(-1)^{i-1}} \tag{1}$$

where S_i represents the combination of i event probabilities such that, $S_1 = \prod_{i=1}^{n}\Phi(\cdot \mid I_i)$, $S_2 = \prod_{i=1,j\in\{i+1,\ldots,n\}}^{n-1}\Phi(\cdot \mid I_i \cap I_j), \ldots, S_n = \Phi(\cdot \mid I_1 \cap I_2 \cap \cdots I_n)$. The alternating multiplication and division of joint probabilities from (1) removes conditional dependencies from the data sets in the form of shared information.

While the removal of duplicate information is straightforward in the theoretical formulation, identification of duplicate information for distributed estimation systems can be difficult in practical implementations. The difficulty is due to the need to recognize correlated information resulting from past fusion events and know the values of their data sets. The information graph (IG) technique presented in [7–9] provides an analytical tool for identifying duplicate information in distributed estimation systems. The approach is a symbolic representation of the collection, propagation, and fusing of data among a set of fusion agents. An example of an IG is shown in Fig. 1, where a simple cyclical communications pattern is demonstrated. Each numbered row of symbols represents the events of a given agent. Within each time step, each agent may perform time updates of estimates, receive sensor data, perform measurement updates, transmit the local estimate to other agents, and fuse estimates received from other agents.

The difficulty with the IG approach is that it is communication pattern dependent—it needs to consider all relevant common priors and to remove the common information at these nodes from the current track update. Determining these nodal connections over a varying network can be difficult and time-consuming. For example, in the simple three sensor cyclic communication network shown in Fig. 1, the resulting formula for the fusion between the first two sensors at time k is [7]

$$p(x) = \frac{1}{c}\frac{p_{1,k}(x)p_{2,k}(x)p_{1,k-3}(x)}{p_{1,k-2}(x)p_{2,k-1}(x)} \tag{2}$$

where c is the normalization constant, $p(x)$ is the conditional probability at node $s1$ after fusion, and $p_{i,k}(x)$ is the conditional probability at node si and time k before fusion. In the case when all probability densities are Gaussian, the fusion formula becomes (see Fig. 1)

$$\begin{aligned} P_k^{-1} &= P_{1,k}^{-1} + P_{2,k}^{-1} - \bar{P}_{1,k-2}^{-1} - \bar{P}_{2,k-1}^{-1} + P_{k-3}^{-1} \\ P_k^{-1}\hat{x}_k &= P_{1,k}^{-1}\hat{x}_{1,k} + P_{2,k}^{-1}\hat{x}_{2,k} - \bar{P}_{1,k-2}^{-1}\bar{x}_{1,k-2} \\ &\quad - \bar{P}_{2,k-1}^{-1}\bar{x}_{2,k-1} + P_{k-3}^{-1}\hat{x}_{k-3}. \end{aligned} \tag{3}$$

In general, to construct the "optimal"[1] fusion formula may require carrying long pedigree information[2] that

[1]The IG approach is optimal when the underlying system is deterministic.

[2]Information includes communication and fusion events history as well as past fusion data.

might not be practical in an environment with limited communication bandwidth [12].

To address the scalability issue, we have developed each of the fusion algorithms described in the following sections for autonomous sensors in arbitrary network conditions. All of these approaches are suboptimal in general but provide adequate performance when basic assumptions are met.

A. Channel Filter

The channel filter approach [13–16] is simpler than IG fusion in that only the first order redundant information is considered. Each channel is defined by a pair of agents—a transmitting agent and a receiving agent. The transmitting agent for a particular channel is responsible for removing redundant information; as such, it needs only keep track of the previous transmission from itself to the receiving node.

However, in a dynamic ad hoc network, the transmitting data may never reach the receiving end because of link uncertainty. Therefore, another idea is to have the receiving agent of a particular channel be responsible for removing the redundant information. In this way, the receiving agent only needs to keep track of the previous data transmitted to or received from the channel at the previous communication time and remove it when combining the current estimates. There is no need to maintain long histories of previous activity. In a sense, this can be considered as a first order approximation to the optimal IG approach.

Specifically, the channel filter fusion equation is given as

$$p(x) = \frac{p_1(x)p_2(x)/\bar{p}(x)}{\int [p_1(x)p_2(x)/\bar{p}(x)]dx} \tag{4}$$

where $p_1(x)$ and $p_2(x)$ are the two probability density functions to be fused (one local and the other received from a particular channel) and $\bar{p}(x)$ is the density function received from the same channel at the previous communication time and is the common "prior information" to be removed in the fusion formula. When both $p_1(x)$ and $p_2(x)$ are Gaussian density with mean and covariance $\hat{x}_1, P_1$ and $\hat{x}_2, P_2$, respectively, the fused state estimate and corresponding covariance error can be written as

$$\begin{aligned} P^{-1} &= P_1^{-1} + P_2^{-1} - \bar{P}^{-1} \\ P^{-1}\hat{x} &= P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2 - \bar{P}^{-1}\bar{x}. \end{aligned} \tag{5}$$

While simpler, it is obvious that dependent information is more likely to be lost in the channel filter when compared with the IG approach. On the other hand, if the time between when that redundancy occurred and the current processing time is relatively long, the impact could be minimal.

B. Naïve Fusion

Naïve fusion is the simplest fusion approach, where it is assumed that the dependency between the density functions is negligible. This fusion approach is the simplest type, but it can be unreliable. The naïve fusion formula can be written as

$$p(x) = \frac{p_1(x)p_2(x)}{\int p_1(x)p_2(x)dx}. \tag{6}$$

For the Gaussian case, the fused state estimate and corresponding error covariance are shown as

$$\begin{aligned} P^{-1} &= P_1^{-1} + P_2^{-1} \\ P^{-1}\hat{x} &= P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2. \end{aligned} \tag{7}$$

Note that the fused track covariance is the inverse of the sum of the inverses of the local track covariance matrices. Thus, because of the lack of common prior information, the fused covariance could be much smaller, which can lead to overconfidence. Also when the common prior has very large covariance, (7) is equivalent to (5).

C. Chernoff Fusion

When the dependency between two distributions is unknown, one idea is to use the Chernoff information [17]. The fusion formula is based on the following:

$$p(x) = \frac{p_1^w(x)p_2^{1-w}(x)}{\int p_1^w(x)p_2^{1-w}(x)dx} \tag{8}$$

where $w \in [0\ \ 1]$ is an appropriate parameter that minimizes a chosen criteria. When the criterion to be minimized is the Chernoff information as defined in the denominator of (8), we call it Chernoff fusion. It can be shown that the resulting fused density function that minimizes the Chernoff information is the one "halfway" between the two original densities in terms of the Kullback Leibler distance [17, p. 312]. In the case when both $p_1(x)$ and $p_2(x)$ are Gaussian, the resulting fused density is also Gaussian with mean and covariance obtained as

$$\begin{aligned} P^{-1} &= wP_1^{-1} + (1-w)P_2^{-1} \\ P^{-1}\hat{x} &= wP_1^{-1}\hat{x}_1 + (1-w)P_2^{-1}\hat{x}_2. \end{aligned} \tag{9}$$

This formula is identical to the covariance intersection (CI) fusion technique [14–15]. Therefore, the CI technique can be considered as a special case of (8). In theory, Chernoff fusion can be used to combine any two arbitrary density functions in a log-linear fashion. However, the resulting fused density may not preserve the same form as the original ones. Also in general, obtaining the proper weighting parameter to satisfy a certain criterion may involve extensive search or computation [18].

D. Shannon Fusion

A special case of (8) is when the parameter w is chosen to minimize the determinant of the fused covariance [18, 19]. In the Gaussian case, it is equivalent to minimizing the Shannon information of the fused density. This is because the Shannon information defined as $I_s = -\int_x p(x)\ln p(x)dx$ can be shown to be equal to $I_s = \frac{1}{2}\ln((2\pi)^n|P|^{1/2}) + n/2$ when $p(x)$ is Gaussian with covariance P [18]. We call this special case the Shannon fusion. Note that with (9), the Shannon information is a convex function of the parameter w, and therefore the maximum is located at the extreme points (either $w = 0$ or $w = 1$). Moreover, in scalar case where both P_1 and P_2 are scalar, the minimum of Shannon information is also located at the extremes [18].

E. Bhattacharyya Fusion

Another special case of (8) is when the parameter w is set to be 0.5. In this case, the denominator of (8) becomes $B = \int \sqrt{p_1(x)p_2(x)}dx$, which is the Bhattacharyya bound. We call the resulting fusion formula, $p(x) = (1/B)\sqrt{p_1(x)p_2(x)}$, the Bhattacharyya fusion. When both $p_1(x)$ and $p_2(x)$ are Gaussian, the fusion equation can be written as

$$\begin{aligned} P^{-1} &= \tfrac{1}{2}(P_1^{-1} + P_2^{-1}) \\ P^{-1}\hat{x} &= \tfrac{1}{2}(P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2) \\ \Rightarrow \hat{x} &= (P_1^{-1} + P_2^{-1})^{-1}(P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2). \end{aligned} \tag{10}$$

Therefore, in the Gaussian case, Bhattacharyya fusion is similar to naïve fusion; the resulting fused covariance is merely twice as big as that of naïve fusion. Note that the fusion equation can be rewritten as

$$\begin{aligned} P^{-1} &= \tfrac{1}{2}(P_1^{-1} + P_2^{-1}) = (P_1^{-1} + P_2^{-1}) - \tfrac{1}{2}(P_1^{-1} + P_2^{-1}) \\ P^{-1}\hat{x} &= \tfrac{1}{2}(P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2) \\ &= (P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2) - \tfrac{1}{2}(P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2). \end{aligned} \tag{11}$$

This formula replaces the common prior information of (5) for the channel filter by the average of the two sets of information to be fused. Namely, $\bar{P}^{-1} \leftarrow \frac{1}{2}(P_1^{-1} + P_2^{-1})$ and $\bar{P}^{-1}\bar{x} \leftarrow \frac{1}{2}(P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2)$. In other words, instead of removing the common prior information from the previous communication, as in the channel filter case, the common information of Bhattacharyya fusion is approximated by the "average" of the two locally available information sets.

In the next section, we derive the analytical performance of channel filter, naïve fusion, and Bhattacharyya fusion in terms of true steady-state mean square error. We will derive the results based on the specific cyclic communication scenario as given in Fig. 1. We will also conduct extensive simulation to evaluate other alternative fusion algorithms.

III. ANALYTICAL PERFORMANCE PREDICTION

As shown in Fig. 1, where at time k we define 1) $\hat{x} \equiv \hat{x}_{k|k}; P_0 \equiv P_{k|k}$ and $\bar{x} \equiv \hat{x}_{k-1|k-1}; \bar{P} \equiv P_{k-1|k-1}$ as the fused state estimates and the associated filter covariances at time k and $k-1$; 2) $\hat{x}_i \equiv \hat{x}_{i,k|k}; P_i \equiv P_{i,k|k}$ as the local updated state estimates and the associated filter covariances; and 3) $\bar{x}_i \equiv \hat{x}_{i,k-1|k-1}; \bar{P}_i \equiv P_{i,k-1|k-1}$ as the local updated state estimates and the associated filter covariances at the previous time instance $k-1$.

Our goal is to find the steady-state mean square error covariance of the fused estimate, namely, $\Omega = \lim_{k\to\infty} E[(\hat{x}_{k|k} - x_k)(\hat{x}_{k|k} - x_k)'] = E[(\hat{x} - x)(\hat{x} - x)']$. In the following, we assume that the dynamic system follows a scalar random walk model, namely, $x_{k+1} = x_k + v_k$ where v_k is a zero mean Gaussian process noise with variance Q. We further assume that the observation model is similar for the three sensors and is linear Gaussian, i.e., $z_{i,k} = x_k + w_{i,k}$ where $w_{i,k}$ is a zero-mean Gaussian measurement noise with variance R_i for sensor i. In the following, we assume that the sensors have the same quality, i.e., $R_1 = R_2 = R_3 = R$. Therefore, in steady state, let $P_i = P$, then $\bar{P}_i = P_{i,k-1|k-1} = P_{i,k|k} = P_i = P$.

A. Channel Filter

With a channel filter, as shown in (5), the fusion equations are written as

$$P_0^{-1} = P_1^{-1} + P_2^{-1} - \bar{P}_{2,k|k-1}^{-1} \tag{12}$$

$$P_0^{-1}\hat{x} = P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2 - \bar{P}_{2,k|k-1}^{-1}\bar{x}_{2,k|k-1}. \tag{13}$$

Equation (13) can be rewritten as,

$$\begin{aligned} A &\equiv P_0^{-1}(\hat{x} - x) = P_1^{-1}(\hat{x}_1 - x) + P_2^{-1}(\hat{x}_2 - x) \\ &\quad - \bar{P}_{2,k|k-1}^{-1}(\bar{x}_{2,k|k-1} - x) \\ &= P^{-1}(\hat{x}_1 - x) + P^{-1}(\hat{x}_2 - x) - (P + Q)^{-1}(\bar{x}_2 - x) \\ &\Rightarrow (\hat{x} - x) = P_0 A \\ &= P_0 P^{-1}(\hat{x}_1 - x) + P_0 P^{-1}(\hat{x}_2 - x) \\ &\quad - P_0(P + Q)^{-1}(\bar{x}_2 - x). \end{aligned} \tag{14}$$

Therefore,

$$\Omega \equiv E[(\hat{x} - x)^2] = P_0 E(AA')P_0'. \tag{15}$$

In the scalar case,

$$\begin{aligned} (\hat{x} - x)^2 &= \frac{P_0^2}{P^2}(\hat{x}_1 - x)^2 + \frac{P_0^2}{P^2}(\hat{x}_2 - x)^2 + \frac{P_0^2}{(P+Q)^2}(\bar{x}_2 - x)^2 \\ &\quad + \frac{2P_0^2(\hat{x}_1 - x)(\hat{x}_2 - x)}{P^2} - \frac{2P_0^2(\hat{x}_1 - x)(\bar{x}_2 - x)}{P(P+Q)} \\ &\quad - \frac{2P_0^2(\hat{x}_2 - x)(\bar{x}_2 - x)}{P(P+Q)} \end{aligned} \tag{16}$$

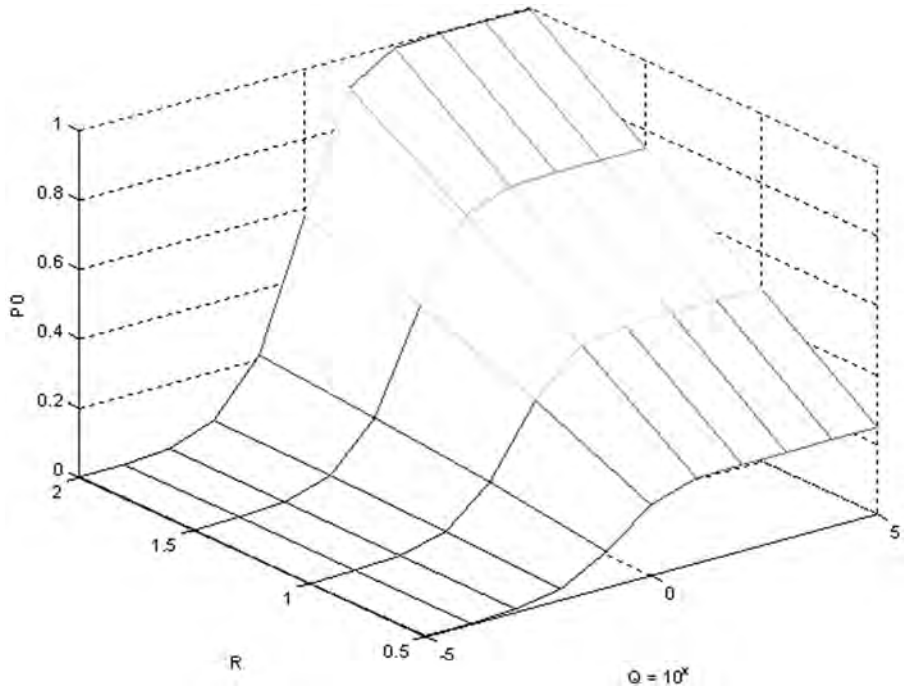

Fig. 2. Steady-state filter variances P and P_0 for various Q and R.

$$\Rightarrow \Omega = \frac{2P_0^2}{P^2}(B+E') + \frac{P_0^2}{(P+Q)^2}(B+Q) - \frac{2P_0^2}{P(P+Q)}(C_1+C_2) \tag{17}$$

where

$$\begin{aligned} E[(\bar{x}_2 - x)^2] &= E[(\bar{x}_{2,k|k-1} - x_k)^2] \\ &= E[(\bar{x}_{2,k-1|k-1} - x_{k-1} - v_{k-1})^2] \\ &= B + Q \end{aligned} \tag{18}$$

$$B \equiv E[(\hat{x}_1 - x)^2] = E[(\hat{x}_2 - x)^2] \tag{19}$$

$$E' \equiv E[(\hat{x}_1 - x)(\hat{x}_2 - x)] \tag{20}$$

$$C_1 \equiv E[(\hat{x}_2 - x)(\bar{x}_2 - x)] \quad \text{and} \quad C_2 \equiv E[(\hat{x}_1 - x)(\bar{x}_2 - x)]. \tag{21}$$

Note that in (17), P_0 and P are the steady-state "filter" variances. They can be obtained by solving the following two equations:

$$P_0^{-1} = P_1^{-1} + P_2^{-1} - \bar{P}_{2,k|k-1}^{-1} = 2P^{-1} - (P+Q)^{-1} \Rightarrow P_0 = P(P+Q)/(P+2Q) \tag{22}$$

$$P = (P_0+Q) - KSK' = (P_0+Q) - \frac{(P_0+Q)^2}{(P_0+Q+R)} = \frac{(P_0+Q)R}{(P_0+Q+R)} \tag{23}$$

where $K = (P_0+Q)/(P_0+Q+R)$ is the steady-state Kalman gain and $S = P_0 + Q + R$ is the steady state innovation variance. From (22) and (23), it can be easily shown that

$$P^3 + (2Q)P^2 + (2Q^2)P - (2Q^2)R = 0. \tag{24}$$

A closed form real solution of the preceding cubic polynomial can be solved and the resulting P_0 as a function of various Q and R is shown in Fig. 2.

Note that the filter variance is not the same as the true mean square error. To obtain the true mean square error as given in (17), we will need to derive each of the three terms listed in (19)–(21). It can be shown that (the details are omitted),

$$B = (1-K)^2\Omega + (1-K)^2 Q + K^2 R \equiv \lambda\Omega + \alpha \tag{25}$$

$$\begin{aligned} E' &= (1-K)^2\{E[(\bar{x}_1' - x_{k-1})(\bar{x}_2' - x_{k-1})] + Q\} \\ &\equiv (1-K)^2[E_p + Q] \end{aligned} \tag{26}$$

$$E_p = \left(\frac{P_0}{P}\right)^2(3E'+B) + \left(\frac{P_0}{P+Q}\right)^2(E'+Q) - \left(\frac{P_0^2}{P(P+Q)}\right)(C_1+C_2+2D) \tag{27}$$

$$\begin{aligned} C_1 = C_2 &= \frac{(1-K)\left(\frac{P_0}{P}B + \frac{P_0}{P}E' + Q\right)}{1 + (1-K)\frac{P_0}{P+Q}} \\ &= \frac{(1-K)(P+Q)}{2(P+Q)-KP}(E'+B) + \frac{(1-K)(P+2Q)}{2(P+Q)-KP}Q \\ &\equiv \eta(E'+B) + \eta' \end{aligned} \tag{28}$$

and

$$D = \eta(2E') + \eta'. \tag{29}$$

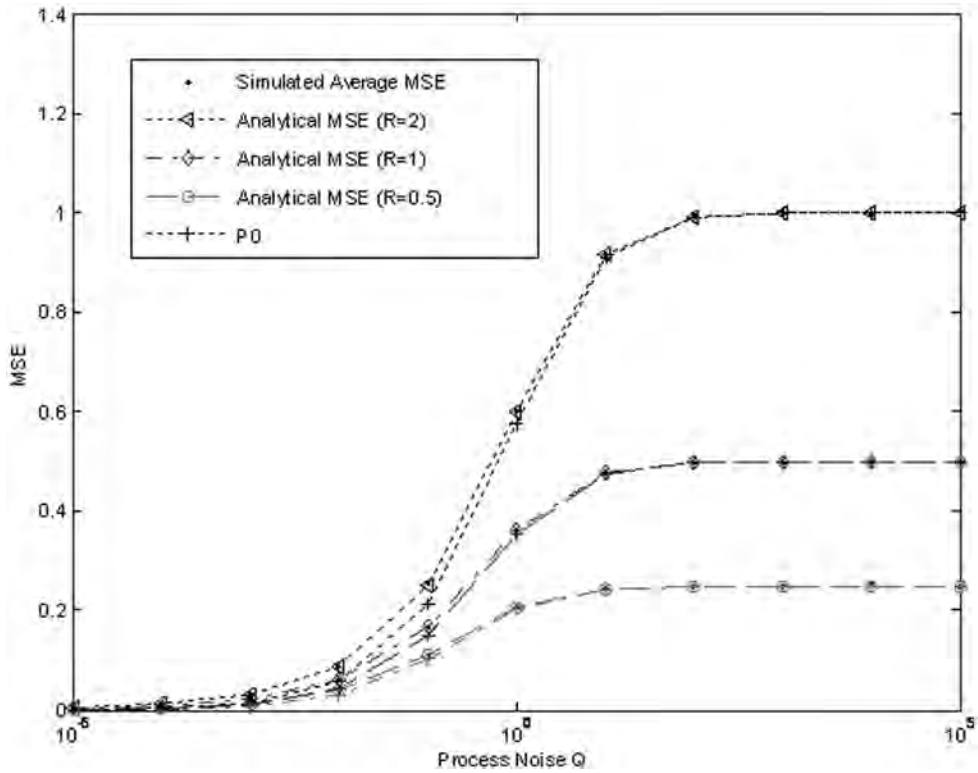

Fig. 3. Comparison of channel filter analytical MSE with simulated MSE (1000 MC trials).

Using relations (25)–(29), (17) can be rewritten as

$$\begin{aligned}\Omega &= \frac{2P_0^2}{P^2}(B+E') + \frac{P_0^2}{(P+Q)^2}(B+Q) - \frac{2P_0^2}{P(P+Q)}(2C)\\ &= \left(\frac{2P_0^2}{P^2} + \frac{P_0^2}{(P+Q)^2} - \frac{4P_0^2}{P(P+Q)}\eta\right)B\\ &\quad + \left(\frac{2P_0^2}{P^2} - \frac{4P_0^2}{P(P+Q)}\eta\right)E'\\ &\quad + \frac{P_0^2}{(P+Q)^2}Q - \frac{4P_0^2}{P(P+Q)}\eta'\\ &\equiv l_1B + l_2E' + l_3 = (l_1 + l_2f_1)B + l_2f_2 + l_3\\ &\equiv m_1B + m_2 = m_1(\lambda\Omega + \alpha) + m_2\\ &\Rightarrow \Omega = \frac{m_1\alpha + m_2}{1 - m_1\lambda}. \end{aligned} \tag{30}$$

Fig. 3 compares the analytical mean square errors (MSE) based on (30) with the average MSE based on 1000 Monte Carlo simulation trials. It is clear that they are in perfect agreement. Fig. 3 also shows that the filter variance P_0 is very close to the true MSE, which indicates that the algorithm behaves well and is reasonably consistent [9].

B. Naïve Fusion

With the notations defined earlier, the naïve fusion equations can be written as

$$P_0 = (P_1^{-1} + P_2^{-1})^{-1} = P/2 \tag{31}$$

$$\hat{x} = P_0(P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2) = (\hat{x}_1 + \hat{x}_2)/2. \tag{32}$$

From (31), $(\hat{x} - x) = [(\hat{x}_1 - x) + (\hat{x}_2 - x)]/2$; therefore,

$$\begin{aligned}\Omega &\equiv E[(\hat{x} - x)^2]\\ &= \tfrac{1}{4}[E[(\hat{x}_1 - x)^2] + E[(\hat{x}_2 - x)^2] + 2E[(\hat{x}_1 - x)(\hat{x}_2 - x)]]\\ &= \tfrac{1}{2}(B + E') \end{aligned} \tag{33}$$

where, as defined before, $B = E[(\hat{x}_1 - x)^2] = E[(\hat{x}_2 - x)^2]$ and $E' = E[(\hat{x}_1 - x)(\hat{x}_2 - x)]$.

From (25), $B = \lambda\Omega + \alpha$, and from (26),

$$\begin{aligned}E' &= E[(\hat{x}_1 - x_k)(\hat{x}_2 - x_k)]\\ &= (1-K)^2\{E[(\bar{x}_1' - x_{k-1})(\bar{x}_2' - x_{k-1})] + Q\}\\ &= \tfrac{1}{4}(1-K)^2(B + 3E' + 4Q)\\ &\Rightarrow E' = \frac{(1-K)^2}{4 - 3(1-K)^2}(B + 4Q) \equiv \mu(B + 4Q). \end{aligned} \tag{34}$$

Therefore, from (25), (33), and (34), we have,

$$\begin{aligned}\Omega &= \tfrac{1}{2}(B + E') = \tfrac{1}{2}(1+\mu)B + 2\mu Q\\ &= \tfrac{1}{2}(1+\mu)(\lambda\Omega + \alpha) + 2\mu Q \Rightarrow \Omega = \frac{(1+\mu)\alpha/2 + 2\mu Q}{1 - (1+\mu)\lambda/2}. \end{aligned} \tag{35}$$

Note that in (31), P_0 and P are the steady-state "filter" variances, which are not the same as the true MSEs. They can be obtained by solving the following two

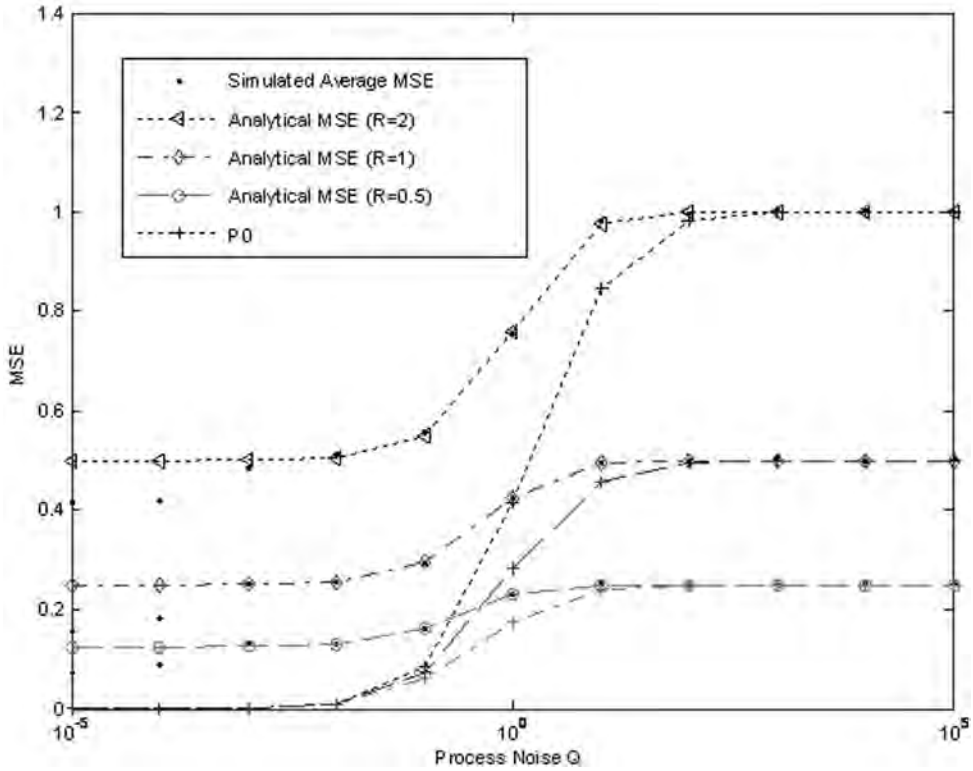

Fig. 4. Comparison of naïve fusion analytical MSE with simulated MSE (1000 MC trials).

equations:

$$P_0^{-1} = P_1^{-1} + P_2^{-1} = 2P^{-1} \Rightarrow P_0 = P/2 \tag{36}$$

$$P = (P_0 + Q) - KSK' = (P_0 + Q) - \frac{(P_0 + Q)^2}{(P_0 + Q + R)} = \frac{(P/2 + Q)R}{(P/2 + Q + R)}. \tag{37}$$

From (36) and (37), it can be easily shown that

$$P^2 + (2Q + R)P - 2QR = 0 \Rightarrow P = \frac{\sqrt{(2Q + R)^2 + 8QR} - (2Q + R)}{2}. \tag{38}$$

Fig. 4 compares the analytical MSEs based on (35) with the average MSE based on 1000 Monte Carlo simulation trials. It is clear that they are very close to each other when the process noise is not very small. However, when the process noise is extremely small ($\leq 10^{-4}$), the simulation results are slightly lower than the analytical prediction. This could be due to numerical round off error caused by the small magnitude of the noise. Fig. 4 also shows that the steady-state filter variances P_0 are significantly smaller than the true MSE, especially when the process noise is not very large. This implies that naïve fusion is too optimistic and has poor filter consistency [11].

C. Bhattacharyya Fusion

As in the naïve fusion case, the Bhattacharyya fusion equations can be written as

$$P_0 = 2(P_1^{-1} + P_2^{-1})^{-1} = P \tag{39}$$

$$\hat{x} = \tfrac{1}{2}P_0(P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2) = (\hat{x}_1 + \hat{x}_2)/2. \tag{40}$$

As in (33)

$$\begin{aligned}\Omega &\equiv E[(\hat{x} - x)^2] \\ &= \tfrac{1}{4}\{E[(\hat{x}_1 - x)^2] + E[(\hat{x}_2 - x)^2] + 2E[(\hat{x}_1 - x)(\hat{x}_2 - x)]\} \\ &= \tfrac{1}{2}(B + E')\end{aligned} \tag{41}$$

where, as defined before, $B = \lambda\Omega + \alpha$ and $E' = [(1 - K)^2/4 - 3(1 - K)^2](B + 4Q) \equiv \mu(B + 4Q)$. Therefore, as in (35)

$$\Omega = \frac{(1 + \mu)\alpha/2 + 2\mu Q}{1 - (1 + \mu)\lambda/2}. \tag{42}$$

Note that the only difference between naïve and Bhattacharyya fusion is in (38), where P_0 and P are the steady-state "filter" variances, which can be obtained by solving the following equation:

$$P = (P_0 + Q) - KSK' = (P_0 + Q) - \frac{(P_0 + Q)^2}{(P_0 + Q + R)} = \frac{(P + Q)R}{(P + Q + R)}. \tag{43}$$

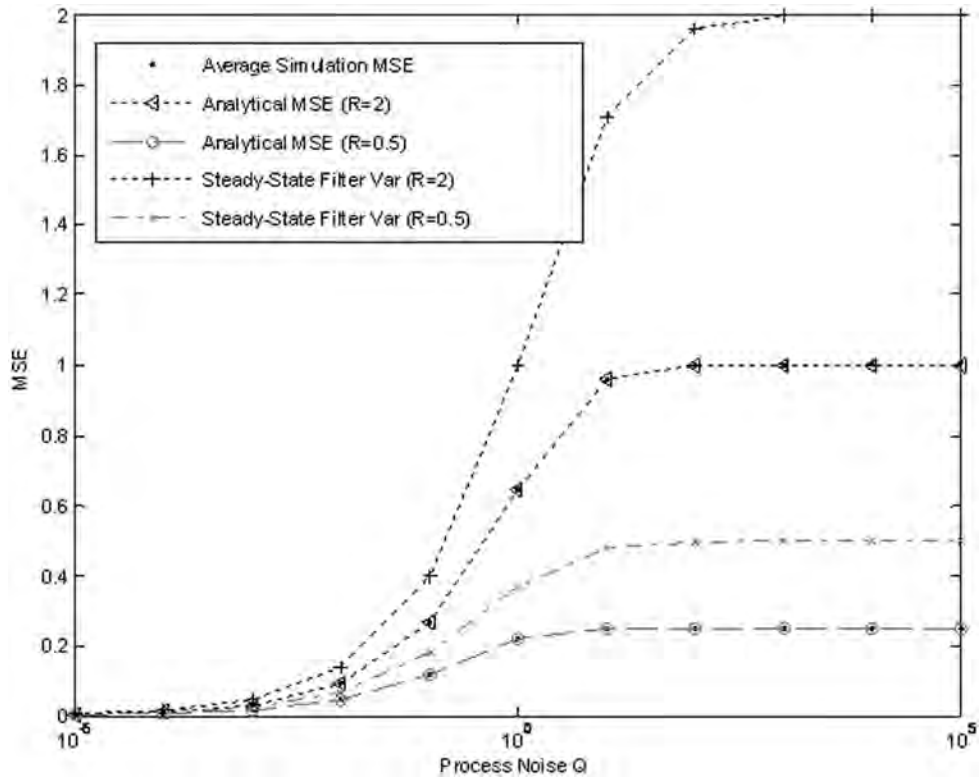

Fig. 5. Comparison of Bhattacharyya fusion analytical and simulated MSE (1000 MC trials).

From (43), it can be easily shown that

$$P^2 + PQ - QR = 0 \Rightarrow P = \frac{\sqrt{Q^2 + 4QR} - Q}{2}. \tag{44}$$

Fig. 5 compares the analytical MSEs based on (41) with the average MSE based on 1000 Monte Carlo simulation trials. Again, they are in perfect agreement. However, as can be seen in the figure, a critical issue with this approach is that the steady-state filter variances are almost twice as large as the true MSE. This indicates that the Bhattacharyya fusion algorithm is too pessimistic and is severely inconsistent.

IV. SIMULATION RESULTS AND DISCUSSION

In addition to the theoretical analysis for channel filter, naïve fusion, and Bhattacharyya fusion, we conducted extensive simulation for Chernoff fusion and Shannon fusion to compare their performances against optimal centralized fusion. The results are shown in Fig. 6. As can be seen, in addition to naïve fusion, Shannon fusion also performs poorly. This is because in the scalar case, Shannon fusion essentially picks the density with smaller variance. Therefore the fusion performance converges to single sensor performance when the sensor qualities are identical.

As shown in Fig. 6, the remaining three algorithms have very similar performance. A closer look (Fig. 7) reveals that channel filter performs close to optimal while Chernoff fusion and Bhattacharyya fusion perform slightly worse. Note that when all sensors have the same quality, Chernoff fusion converges to Bhattacharyya fusion.

We then evaluate the fusion algorithms with different sensor qualities. Instead of homogeneous quality as in the previous case, the sensor measurement error variances are set as 0.5, 1.0, and 2.0 for the three sensors, respectively. The results are shown in Fig. 8, which compares the performance of channel filter, Chernoff fusion, and Bhattacharyya fusion versus optimal fusion. From the figure, it is clear that channel filter performs the best, Bhattacharyya fusion performs slightly worse, while Chernoff fusion performs the worst among the three, particularly when the process noise is large.

To simulate the stochastic nature of the communication link, we model the reliability of each link with a probabilistic measure. For example, a link with 0.5 reliability means that the information will pass through the channel only 50% of the time. We then test the three fusion algorithms and their robustness under various link reliabilities. Because all algorithms under consideration are scalable and autonomous, no additional changes are necessary in the algorithms for the test. The results in Fig. 9 show that the performances are in general proportional to the communication quality, which is quite intuitive. The results also show that all three algorithms are quite stable and they perform according to expectation.

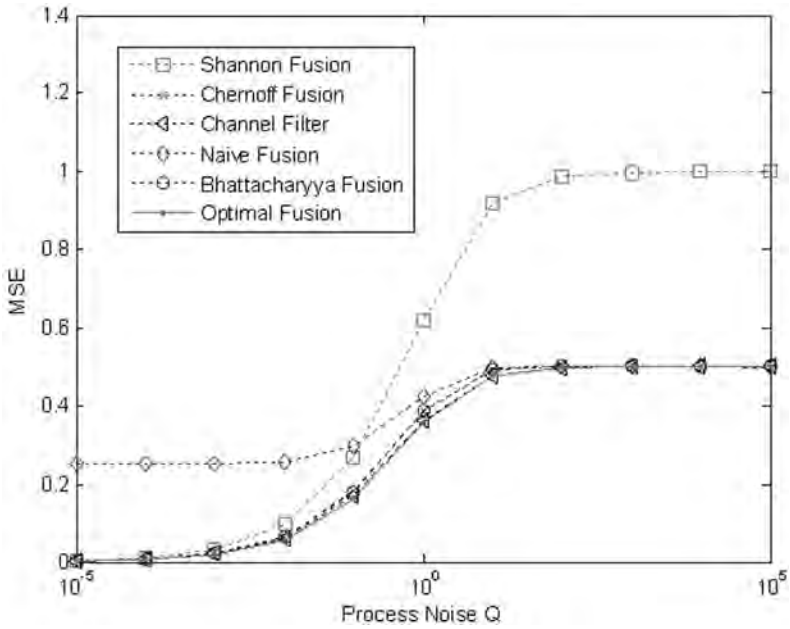

Fig. 6. Comparison of alternative fusion algorithms with optimal fusion algorithm ($R_1 = R_2 = R_3 = 1$).

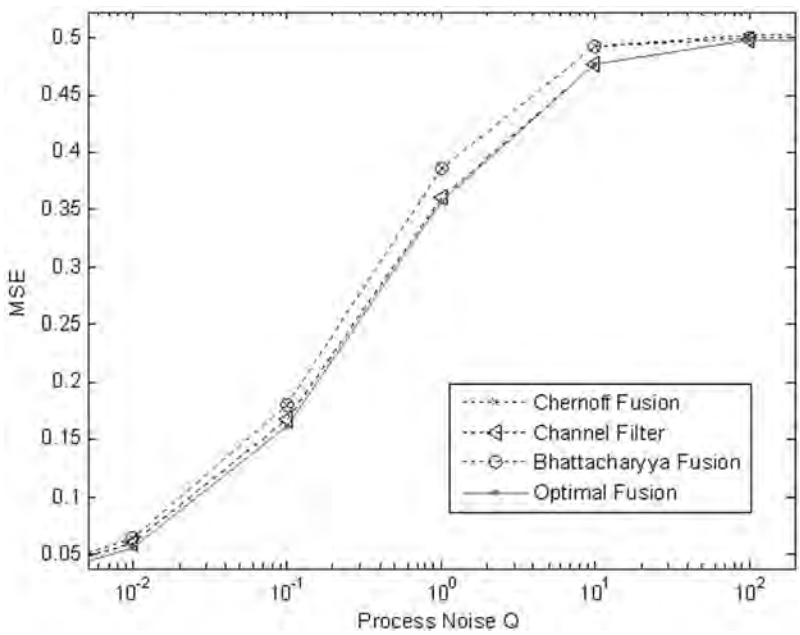

Fig. 7. Comparison of channel filter, Chernoff fusion, and Bhattacharyya fusion ($R_1 = R_2 = R_3 = 1$).

It should be noted that channel filter, while requiring a one-step memory to retrieve and remove the common prior information in each channel, has a rather simple implementation. On the other hand, the Chernoff fusion algorithm, in addition to its poor filter consistency, needs significantly more computation to search for the optimal weighting factor. Our preliminary experiments show that channel filter is at least one order of magnitude faster than the Chernoff fusion. Further investigation is needed to compare the trade-offs between these promising algorithms in a more reliable manner.

V. SUMMARY

In this paper, we focus on the analysis and comparison of several scalable algorithms for distributed fusion in a cyclic communication sensor network. Specifically, we evaluate the performance of channel filter fusion, naïve fusion, Chernoff fusion, Shannon fusion, and Bhattacharyya fusion algorithms. We also compare their performance to "optimal" centralized fusion algorithms under a specific communication pattern.

The results show that naïve fusion and Shannon fusion perform poorly while several other scalable

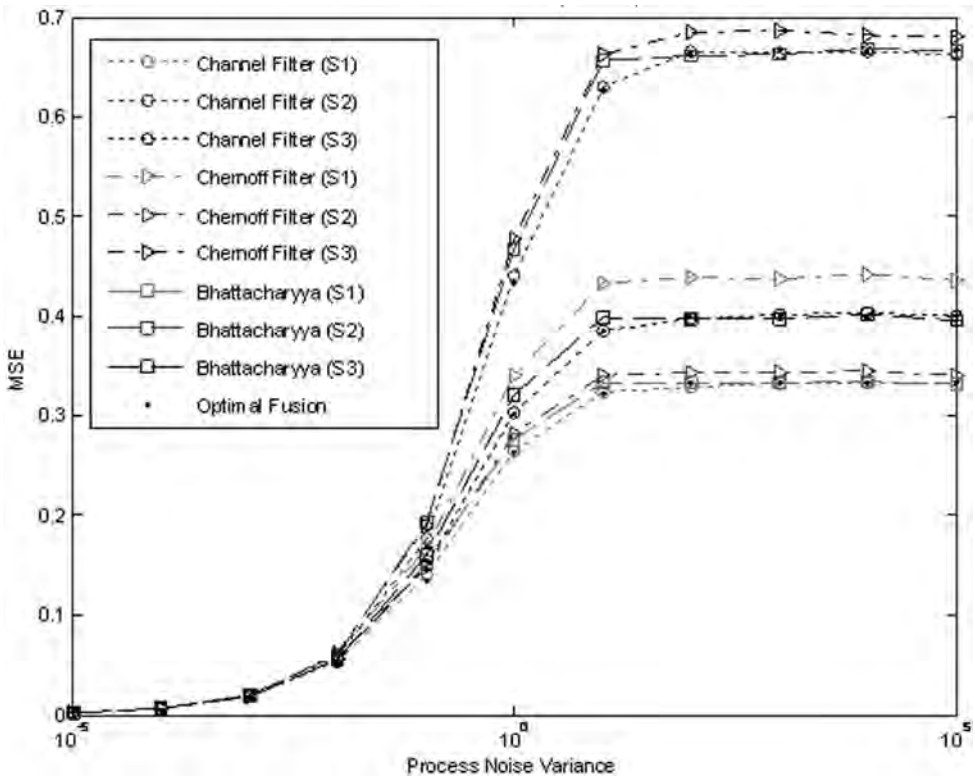

Fig. 8. Channel filter, Chernoff fusion, and Bhatacharyya fusion versus optimal fusion with sensors of different qualities ($R_1 = 0.5$, $R_2 = 1.0$, $R_3 = 2.0$).

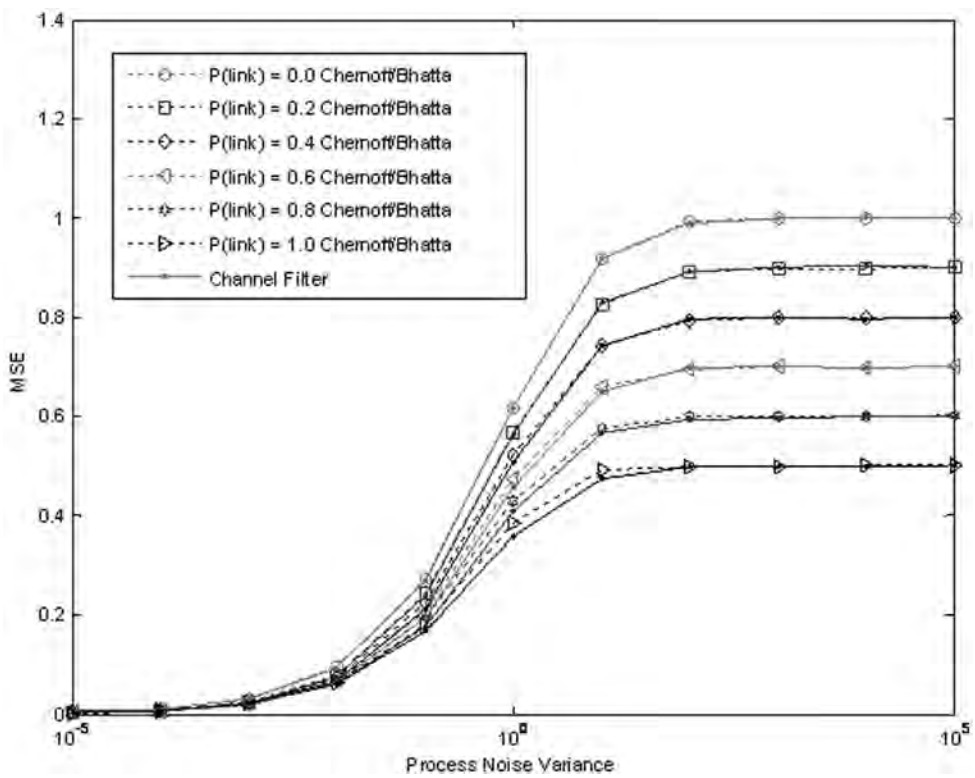

Fig. 9. Channel filter versus Bhattacharyya fusion with various communication link qualities ($R_1 = R_2 = R_3 = 1$).

algorithms including channel filter, Chernoff fusion, and Bhattacharyya fusion, require minimum communication and perform fairly well. Their performance is comparable with that of the optimal fusion algorithm. In particular the channel filter fusion, representing a first-order approximation to IG fusion, works surprisingly well and has been shown to be the only "consistent" fusion algorithm.

One of the future research directions is to extend and validate the results to more general network scenarios. In particular, to address the real world network-centric tracking and fusion problems. It is important to consider heterogeneous sensors with different sampling interval and error characteristics under dynamic communication topology and constraints. It is also useful to develop theoretical analysis for specific algorithms whenever possible for a given network scenario.

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