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Adaptive reliability satisfaction in wireless sensor networks through controlling the number of active routing paths

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ABSTRACT

The number of active paths in multipath routing scenarios (with concurrent data transmission over the established paths) affects the provided reliability degree as well as the imposed overhead of path management. Since the reliability of individual links varies over the time, adaptively setting the sufficient number of active paths turns out to be essential. In this paper, we first propose a Reliability Estimation for WSNs (RE-WSNs) algorithm, based on ordered binary decision diagram (OBDD) data structure, which gives the network reliability in terms of the reliability of all individual links. Second, we propose a novel algorithm called adaptive reliability satisfaction–multipath routing (ARS–MR) which adaptively sets the sufficient number of active paths, aiming at keeping the network reliability within a desired quantitative range and minimizing path management overhead. In activation/inactivation process it further takes into account energy efficiency considerations. The proposed ARS–MR algorithm can be used in conjunction with any arbitrary multipath algorithm in WSNs. Simulation results with NS-2 reveal that ARS–MR is quite successful in timely reacting to variations of links reliability. Indeed, it manages the number of active paths and keeps the reliability of the network satisfactory over the course of network lifetime.

1. Introduction

Recent advances in wireless communications have led to a surge of attention to wireless sensor networks (WSNs). WSNs are composed of hundreds to thousands of small wireless sensors distributed in a wide area depending on the requirements and scale of the application in-hand. Sensors in a WSN are responsible for collecting information from sensing fields and transmitting the data to one or several specific nodes called sink nodes. The role of a sink is inter-connecting the sensor network to other networks. Due to their extensive industrial attraction, WSNs are getting lots of interest in the recent years. Several scientific and technical challenges should be addressed in these networks. Some of these challenges and state of the art trends can be found in [1–3].

Fig. 1 shows a typical sensing scenario in which sensing nodes (namely source nodes) transmit what they have sensed to the sink via other sensor nodes. In critical sensing applications, the reliability of such a transmission is a severe challenge in WSNs. The reliability of complex systems is very essential since any damage to elements may cause detrimental outcomes [4,5]. Typically, reliability is defined as capability of a system or an element to do its functionality under special circumstances. Likewise, reliability plays an important role in the performance of WSNs. Therefore, any novel approach concerning performance improvement in WSNs should estimate reliability at the very first steps. Evaluation of reliability has been studied extensively in literature of traditional computer networks (wired networks). However, some of the unique characteristics of WSNs make the existing techniques inefficient [6,7]. There are two general methods to improve the reliability of data transmissions over computer/telecommunication networks as follows [8]:

a. Retransmission: In this approach, the sink transmits an acknowledgment back to the source when a data packet is received successfully. If the source does not receive an acknowledgment before a timeout, it re-transmits the data packet. Therefore, in this mechanism, not only an extra buffer is required, but the traffic load, energy consumption and delivery delay are increased as well.
b. Replication: In this approach, the sender node creates multiple identical copies of a packet and sends them over different disjoint paths. In order to send the replications through different paths, a kind of multipath routing algorithm is needed [9,10]. In general, there are two major paradigms: 1) the data is transmitted concurrently over several paths; and 2) the data is sent only over a single path (called primary path) but other established paths are used as back-ups.

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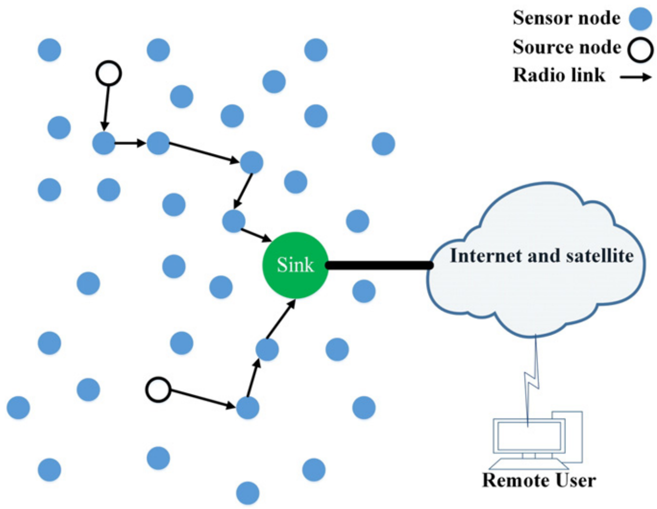

Fig. 1. Sensor nodes scattered across a sensor field.

In this paper, reliability provisioning is pursued based on first technique of replication (i.e., concurrent transmission).

There are many definitions of reliability depending on the problem in-hand [7,11,12]. For the sake of clarification, we first define that of ours; the formal definition will be introduced in Section 3.1. Intuitively, we consider the network to be in two extreme modes: reliable and unreliable. A network is regarded reliable if *each source has at least one path toward the sink*. A network is said to be unreliable *when at least one source loses its connection with the sink*. We consequently define *network reliability* as the probability of the network to be in the reliable mode. It should be noted that in most of previous works, reliability has been studied just for individual source–sink connections, whereas our definition includes the reliability of the network as a whole.

When a multipath routing is used for satisfying reliability, it is important to adaptively determine the right number of active paths. In the previous works, although the number of paths can be limited (e.g., maximum 3 paths), it is not set based on quantitative reliability requirements. We limit the number of active paths based on path availability aiming at reducing the overhead of path maintenance. Here two cases are probable. On the one hand, if the number of active paths is more than enough, an additional redundant overhead is burdened on the network. On the other hand, if the number of active paths is less than enough, reliability is not satisfied. Besides, the more paths are used, the more energy is consumed. Therefore, an adaptive and dynamic mechanism is needed to determine the sufficient number of active paths in the entire network (all source–sink connections).

The contribution of this paper is two-fold. First, we propose a novel approach for estimating the *network reliability*. This technique is called reliability estimation for WSNs (RE-WSNs) hereafter. Our reliability analysis is based on ordered binary decision diagram (OBDD) which is commonly used for reliability analysis of wide range networks such as computer, communication and power networks, or even electrical power systems [13–15]. Second, we propose an adaptive algorithm called adaptive reliability satisfaction–multipath routing (ARS–MR). This algorithm determines the right number of active paths within the whole network (i.e., between all source–sink pairs) in a way that the expected network reliability range is satisfied and the unnecessary path management overhead is avoided at the same time. In the ARS–MR, sink node is responsible for making decision on the number of active paths. Indeed, the sink periodically estimates reliability using the proposed RE-WSNs and tries to adaptively set the sufficient number of active paths in response to changes in links' and paths' reliability during the network lifetime. Moreover, it concerns the energy efficiency of active paths. ARS–MR can be employed along with any multipath protocol in which identical copies of data are concurrently forwarded over several paths. To the best of our knowledge, our work is the first one in the literature of WSNs which proposes an adaptive quantitative reliability provisioning algorithm based on OBDD.

The rest of the paper is organized as follows. Section 2 presents a review of related works. Section 3 presents some preliminaries. Section 4 outlines RE-WSN design and its characteristics. Section 5 explains the mechanism of the proposed algorithm to satisfy reliability (i.e., ARS–MR). Section 6 presents the simulation results and finally, we provide conclusion and the outline of future works in Section 7.

2. Related works

In this section we review the related works into two categories: 1) the literature concerning path reliability, i.e., the reliability of a given source-to-sink connection. 2) The literature of the whole network reliability which is more relevant to our work. Just bear in mind that in the second category, the reliability of the entire network consisting of several source-to-sink connections is the main concern not merely the reliability of a given connection.

2.1. Path reliability

Recently there are plenty of works taking advantage of multipath routing for reliability satisfaction. In RFTM [16] an on-demand routing protocol has been proposed aiming at increasing the reliability in WSNs. In the RFTM, for each available path, the sink determines the suitable coding rate. The sink makes its decision based on some parameters including the number of path hops, the minimum amount of remained energy of nodes and the reliability of the paths. The latter is obtained by multiplying the reliability of links composing the path. In [17], energy consumption is the main metric for the Reliable Energy Aware Routing (REAR). This protocol proposes an energy reservation scheme in routing data toward the sink. In order to increase the network reliability, a backup path from the source to the sink is established for each primary path. Nonetheless, this approach does not propose any algorithm for determining the number of paths in an adaptive way. Split Multipath Routing (SMR) [18] concentrates on creating and maintaining the maximum number of independent paths while distributes the ongoing traffic between two paths out of all paths. However, no quantitative threshold for target reliability is considered in that paper. In [19], the authors have suggested an algorithm utilizing several paths wherein a path having the most residual energy is chosen as the primary path and the others are set as back-up paths. When residual energy over the primary path becomes less than that of the back-up paths, the primary path is substituted.

These works are different than ours in that they consider reliability of given source-to-sink connections while our work considers the *network reliability* as a single metric. We also tune the network reliability through controlling the degree of multipath routing which has not been examined in this literature.

2.2. Network reliability

In the literature, few works have studied network reliability. In [20], a model for estimating reliability and lifetime based on Monte Carlo scheme has been proposed. The authors consider a randomly deployed hierarchical clustered architecture for the reliability modeling. Each cluster has a cluster-head which is chosen among the nodes of the cluster by a proposed scheme. A node may whether take the role of a sensor (gathering, transmitting and receiving data) or a relay (only transmitting). Reliability is defined as the probability of sensing every point in the sensed field by at least k nodes and then existence of at least one path from each k nodes to the base station [20]. Simulation results have revealed that node density and role assignment are two