Robust multi-path routing for dynamic topology in wireless sensor networks

Abstract Wireless sensor networks are being widely researched and are expected to be used in several scenarios. On the leading edge of these, on-demand, high-reliability, and low-latency routing protocol is desirable for indoor environment applications. This article proposes a routing scheme called robust multi-path routing that establishes and uses multiple node-disjoint routes. Providing multiple routes helps to reduce the route recovery process and control the message overhead. The performance comparison of this protocol with dynamic source routing (DSR) by OPNET simulations shows that this protocol is able to achieve a remarkable improvement in the packet delivery ratio and average end-to-end delay.

Keywords multiple node-disjoint routes, finite-state Markov channel model, high-reliability, low-latency

1 Introduction
The vision of Ubiquitous Computing described by Mark Weiser in his article [1] is based on the idea that future computers will progressively combine with their environment until they become completely invisible to the user. With technology development, the trend will not remain only as an imagination. In the recent years, the revolution has resulted in considerably smaller and cheaper computers, and single purpose computers with embedded sensors are almost available from both economical and theoretical viewpoints. Wireless sensor networks (WSN) [2, 3] are becoming a reality, and therefore, the related aspects such as routing protocols have become an important area of research.

So far, several routing protocols have been developed for wireless Ad-hoc networks or sensor networks. Reactive routing algorithms such as Ad-hoc on-demand distance vector (AODV) protocol [4] and dynamic source routing protocol (DSR) [5] maintain routing information for a small subset of possible destinations, namely those currently in use. However, route rediscovery broadcasts can lead to significant delays and energy consumptions in a dynamic sensor network with a large network diameter. Hierarchical routing protocols, such as low-energy adaptive clustering hierarchy (LEACH) [6], hybrid energy-efficient distributed clustering (HEED) [7], etc., are suitable for large-scale networks to monitor outdoor environments with periodical data transmissions.

The aim of this study is to determine a suitable routing protocol for indoor environments, such as meeting rooms, exhibition halls, gymnasiums, etc. Under the circumstances, low-latency and robust on-demand data transmissions become more important than other requirements such as the energy efficiency since the battery of the sensor node can be recharged or replaced in such cases. We refer to the new protocol as robust multi-path routing protocol. The primary design goal is to provide efficient fault tolerance, that is, faster and more efficient recovery from route failures in dynamic networks. To achieve this goal, the proposed protocol enables the path accumulation feature in route Interest/ACK packets and computes multiple loop-free, long-lived, and node-disjoint paths. A particular property of flooding is used to ensure several node-disjoint paths found within a single route discovery.

2 Finite-state Markov channel model
First, suppose a set of $N$ nodes each with transmission range $r$ is uniformly randomly placed in an area $A$ [8]. The nodes move independently in this area.

Second, suppose each node has the same transmission power with a constant value. The signal attenuation is only related to the distance between two nodes.

Third, divide the range of the received signal strength into a finite number of intervals, each corresponding to a certain length of distance. Let $0 = D_0 < D_1 < D_2 < \ldots < D_k = \infty$ be the thresholds of distance. The node communication range $r$ belongs to the set $\{D_j\mid j = 0, 1, 2, \ldots, k\}$. The channel quality is then supposed to be in state $S_k$, $k = 0, 1, 2, \ldots, k - 1$ if the distance between two nodes is in the interval $[D_k, D_{k+1})$. Let $S = \{S_0, S_1, \ldots, S_k\}$ denote a finite set of channel states.
Finally, for indoor environments where nodes move slowly, a suitable sample period can be chosen to measure the received signal strength so that the change of distance between any pair of nodes will not exceed one unit in a sample period. Thus, if the channel quality is in the state $S_k$ at a sample time, then it is likely in the state, $S_{k+1}$, $S_k$, or $S_{k-1}$ for the next sample period. Apparently, the set of channel quality $S$ forms a finite-state Markov chain.

Under these circumstances, the channel quality of one link can be mapped into the distance between two nodes [9]. The link with shorter distance is considered to be better with longer lifetime. A path from source to destination consists of a set of consecutive links defined as $P_{s \rightarrow d} = \{l_{s \rightarrow e_1}, l_{e_1 \rightarrow e_2}, \ldots, l_{e_{n-1} \rightarrow d}\}$, where $l_{s \rightarrow e_1}, l_{e_1 \rightarrow e_2}, \ldots, l_{e_{n-1} \rightarrow d}$ represent links between the source and destination. The quality of the path can then be determined by a factor, namely $\max\{D_{s \rightarrow e_1}, D_{e_1 \rightarrow e_2}, \ldots, D_{e_{n-1} \rightarrow d}\}$, where $D_{s \rightarrow e_1}, D_{e_1 \rightarrow e_2}, \ldots, D_{e_{n-1} \rightarrow d}$ refer to the distances between adjacent nodes. Apparently, if the factor is small, the entire path has a long lifetime and can be a robust route. This principle will be used in the selection of node-disjoint paths.

### 3 Robust multi-path routing protocol

A routing protocol called robust multi-path routing is developed for dynamic topology. The main goal of this routing protocol is to build multiple long-lived node-disjoint paths with a low routing overhead during a route discovery in the dynamic topology scenario. Path accumulation is enabled in Interest packets (an Interest packet that contains several interested attributes of the detected events is initiated by a user device). When the Interest packets are generated or forwarded by the nodes in the network, each node appends its own address and distance between the former node and itself to the Interest packets. When an Interest packet arrives at its destination (sensor node, which matches certain attributes in an Interest packet), the destination is responsible for judging whether or not the routing path is a long-lived node-disjoint path and delivers an ACK packet to the source node in the reverse route when the most long-lived path is established. As an example, consider five nodes $A$, $B$, $C$, $D$, and $E$ as shown in Fig. 1. Node $A$ (user) needs information of certain events (node $E$ detects the event). It initiates an Interest packet with certain attributes and broadcasts it in its communication range. Node $B$ receives the Interest packet, appends its own address and distance factor to the packets, and forwards it. Similarly, when node $C$ and node $D$ receive the Interest packet, they append their address and distance factor to it and forward the packet.

![Signalling procedure and data transmission](image)

Several unique characteristics of this routing protocol are introduced in the following sections.

#### 3.1 Particular flooding for decreasing routing overhead

Overhead here is defined in terms of the routing protocol control messages that consume both channel bandwidth as well as the battery power of nodes for communication/processing. A unique strategy [10] is used to decrease the broadcast overhead. When a node receives an Interest packet for the first time, it checks the path accumulation list from the packet and calculates the number of hops from the user to itself and records the number as the shortest number of hops in its cache. If the node receives the Interest duplicate again, it computes the number of hops from the user to itself and compares it with the number of the shortest hops recorded in its cache. If the number of hops is larger than the shortest number of hops, the node drops the Interest packet. Otherwise, the node appends its own address to the route path list of the Interest packet and broadcasts the packet to its neighboring nodes.

Each intermediate node uses the approach with low routing overhead to propagate and discard packets. Therefore, only part of packets can reach the destination when compared with the flooding manner. However, not all packets that arrive in the destination are long-lived and node-disjoint. The long-lived node-disjoint paths must be selected among these.

#### 3.2 Selecting node-disjoint paths

When the diffusion process is complete, the factor $Q_{s \rightarrow d} = \max\{D_{s \rightarrow n_1}, D_{n_1 \rightarrow n_2}, \ldots, D_{n_{n-1} \rightarrow d}\}$ (as mentioned in Sect. 2) of each available path is computed. The path with the smallest factor is considered to be the most long-lived and the destination records the list of node IDs for the entire route path in its cache and sends an ACK packet that includes the route path towards the user along the reverse route. Then, the next long-lived path (with the next smallest factor in the remaining available paths) is selected. The destination compares the entire route path to all the existing node-disjoint route paths in its cache. If there is no intermediate node between the route path and any node-disjoint route path recorded in the destination’s cache, the route path
satisfies the requirement of the node-disjoint feature and is recorded in the destination’s cache. Otherwise, the route path is discarded. Similarly, other long-lived node-disjoint paths are chosen. After this procedure, on-demand data transmissions will occur when sensor nodes detect interesting events.

**Algorithm 1** An algorithm for selecting node-disjoint paths

Begin

Available path set \( P = \{p_1, p_2, \ldots, p_s\} \);

Quality of the path \( p_i \) is \( Q_i \);

while \( P \neq \emptyset \) do

Find \( p_j \) with \( Q_j = \min \{Q_q | p_q \in P\} \);

Compare \( p_j \) with existing node-disjoint paths;

if \( p_j \) is another node-disjoint path then do

Add \( p_j \) as node-disjoint path into cache;

else do Drop \( p_j \);

end

\( P = P - \{p_j\} \)

End

### 3.3 Data delivery and route error handling

The sensor node collects data according to the requirement in the Interest packet and then sends data packets through the shortest path. Each node in the route path unpacks the head of the data packet and obtains the next hop node’s ID and then forwards the data packet as shown in Fig. 1. When a node fails to deliver the data packet to the next hop of the route (by receiving a link layer feedback from IEEE 802.11 [11] or not receiving passive acknowledgments [12]), it considers the link to be disconnected and sends a route error (RERR) packet [13] to the upstream direction of the route. The RERR message contains the route to the source (sensor node, which detects and broadcasts data packets), and the immediate upstream and downstream nodes of the broken link. Upon receiving this RERR packet, the source removes the entry in its route table that uses the broken link and selects another route in its cache, and thus the route rediscovery process is reduced. Since these routes are node-disjoint, if one of these routes fails, it will not affect the other route paths. If all routes in the sensor node’s cache fail, a route rediscovery process is initiated by sending a route request packet to the user. It can be proved that an improvement of network performance (high packet delivery ratio) can be achieved while using this robust multi-path routing in the dynamic topology scenario.

### 4 Performance evaluation

#### 4.1 Simulation environment

The performance of the following protocols are evaluated and compared:

1) Robust multi-path routing protocol, which builds multiple node-disjoint paths with a low routing overhead during a route discovery. 

2) DSR: dynamic source routing protocol, which uses single path.

A detailed simulation model based on OPNET is implemented. The simulations are done on a uniform topology consisting of 10 user devices and 50 sensor nodes spread in a square area of 100 m×100 m. The radio range of each device is fixed as a constant (20/30 m were used in the simulation procedures) and the channel capacity is 1 Mb/s. 

The random waypoint model [14] is used to model mobility. Here, each user device starts its journey from a random location to a random destination with a constant speed (selected from 0, 1, 5, 8, and 10 m/s in this simulation). Once the destination is reached, another random destination is targeted after a pause. Here, only the continuous mobility case (i.e., no pause) is considered.

Each user device has a random access time to the network and then initiates a service request. The sensor nodes detecting interesting events are traffic sources that are continuous bit-rate (CBR). Only 512 byte data packets are used. The packet sending rate is set to 1 packet/s. All traffic sessions (user/sensor pair) are established at random times close to the beginning of the simulation run and stay active until the end. Simulations are run for 100 simulated seconds. Each data point represents an average of 20 runs with identical traffic models, but different randomly generated network topologies.

### 4.2 Simulation result

The following performance metrics [15] are evaluated:

1) Packet delivery ratio—ratio of the data packets delivered to the user to that generated by the CBR sources. This is the most important for best-effort traffic.

2) Average end-to-end delay of data packets—this includes the delays caused by route discovery, propagation delay, and transfer times.

The following figures (Figs. 2–5) show the performance metrics as a function of mobility. The speed of the user device is varied from 0 m/s to 10 m/s. A speed of 0 m/s corresponds to a static network. The performances of both the proposed protocol and DSR are similar in the static case. Their performance differences, however, become more apparent at high speed.
Fig. 2  Packet delivery ratio when the radio range is set to 30 m

Fig. 3  Packet delivery ratio when the radio range is set to 20 m

Fig. 4  Average end-to-end delay when radio range is set to 30 m

Fig. 5  Average end-to-end delay when radio range is set to 20 m

Figures 2 and 3 show the throughput of each protocol in packet delivery fraction. The packet delivery ratio is obtained by dividing the number of data packets correctly received by the user devices by the number of data packets originated by the sensor nodes. As expected, the ratio of packets delivered goes down for both schemes. However, this approach loses fewer packets than DSR in mobile cases, because the proposed routing protocol will have other available routes to the user device when one route is broken. It can still deliver data packets provided that one of the remaining routes stays connected. It can also be observed from the results that the network performance in Fig. 2 outperforms that in Fig. 3. The reason is that there will be more node-disjoint routes prepared for sending data packets when sensor nodes have a larger communication range. In this simulation, when the communication range is set to 30 m, there are about 5 routes available. For the case of 20 m, only about 2 routes exist.

There is a tremendous reduction in the average end-to-end delay with this approach as shown in Figs. 4 and 5. The improvement in delay is usually more than 60%. This is because the availability of alternate routes on route failures eliminates the route discovery latency that contributes to the delay. DSR yields longer delays in reconstructing routes, and the period of time the data packets are buffered at the sensor node during route recovery results in larger end-to-end delays. The average delay in Fig. 4 is lesser than that in Fig. 5, because the average length of routes for delivering data packets is longer when the communication range is small. When a 30-meter communication range is used, the average number of hops is about 2. For the case of 20 m, the data packets are sent by almost 4-hop routes.

5 Conclusions

Multi-path routing can be used in on-demand protocols to achieve fast and efficient recovery from route failures in highly dynamic wireless sensor networks. In this article, an on-demand, robust, multi-path routing protocol has been proposed. A particular flooding strategy is used to reduce the control overhead and determine multiple node-disjoint routes within a single route discovery.

The performance of this routing protocol has been studied relative to DSR. The study indicates that the proposed protocol outperforms DSR because multiple routes provide robustness to the mobility. The performance difference becomes evident as the mobility degree increases. This approach has considerably fewer packet drops when compared with DSR. It is also observed that the approach offers a significant reduction in the average end-to-end delay. In general, it always offers a superior overall routing performance than DSR in a variety of mobility conditions.
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References


Biographies: HUANG Ping, from Beijing, M. S. Candidate in Beijing University of Posts and Telecommunications, interested in wireless sensor networks and cellular Ad-hoc relay.

TIAN Hui, from Henan, professor in Beijing University of Posts and Telecommunications, interested in mobile Ad-hoc networks and B3G system.

ZHANG Ming, from Dalian, M. S. Candidate in Beijing University of Posts and Telecommunications, interested in wireless sensor network.

ZHANG Ping, from Shanxi, professor in Beijing University of Posts and Telecommunications, interested in broadband wireless communication and B3G system.