***Abstract*—In disaster management wireless sensor networks, routing holes may occur due to various reasons such as the presence of obstacles (e.g., lakes, rivers, mountains) or external forces (caused by fire, earthquake, flood, ...). The traditional scheme for bypassing holes is to forward packets along the holes' perimeter. However, this scheme leads to two serious problems: data concentration around the hole boundaries and routing path enlargement. Recently, several approaches have been proposed to address these two problems, wherein a common idea is to form forbidden areas around the holes from which packets are kept to stay away. Unfortunately, most of the protocols proposed so far address only special cases where either the network contains only one hole or the sources and the destinations stay fairly far from the holes. In this paper, we focus on the general case where the network may contain multiple holes and the sources/destinations may stay in the vicinity of the holes. We then propose a hole bypassing protocol which can balance the traffic over the network while ensuring the constant stretch property of the routing path. The theoretical analysis proves that the routing path stretch of the proposed protocol can be controlled to be as small as $1 + \epsilon$ (for any predefined $\epsilon > 0$), and the simulation experiments show that our protocol strongly outperforms state-of-the-art protocols in terms of load balancing.**

I. Introduction

Recent years have witnessed a great growth of wireless sensor networks (WSNs) in disaster management [1], [2], [3], [4]. A wireless sensor network is comprised of many tiny sensor nodes [1] equipped with the capabilities of sensing, wireless communicating and data processing. Typically, the sensor nodes collect information (e.g., temperature, humidity, ...) about the surrounding environment and transfer the sensory data to the base station(s) using multihop wireless communication. Therefore, one of the most critical issue in WSNs is how to route all packets to the destinations correctly. In disaster management applications, factors, such as hash environmental conditions (e.g., the presence of lakes, rivers, mountains, buildings, ...), the external forces (e.g., caused by fire, earthquake, flood, ...) may form void areas where there is no working sensor (i.e., these void areas are also named as *holes*). The occurrence of the holes poses many challenges to the routing protocol. The traditional scheme for bypassing the holes is to utilize perimeter routing [5] where the packet is forwarded along the hole perimeter whenever arriving at a node on the hole boundary. However, this approach may incur with two serious problems. The first one is the data concentration around the hole boundary which may lead to a quick energy depletion on the hole boundary nodes. The second one is the enlargement of routing paths, specifically when the hole perimeter contains many concave regions. To deal with these two problems, a great effort has been done, wherein one of the common approaches is to create a forbidden are around every hole from which all packets are kept to stay away. The information of these forbidden areas is disseminated to the surrounding area to establish a hole awareness. This hole awareness is then utilized to discover detour routes [6], [7], [8], [9]. Unfortunately, most of the protocols proposed so far address only the cases when both the source and the destination stay fairly far from the holes. In the cases where the source node or the destination node or both of them reside in the vicinity of holes, the existing approaches still keep using the traditional perimeter routing algorithm (i.e., forwarding the packet along the hole boundary). Consequently, the two problems mentioned above remain unsolved.

[1]In this article, the words node, sensor and sensor node are used interchangeably.

LVGR [10] is the first work addressing the problem of routing in the vicinity of the holes. The authors of this work exploit the visibility graph to construct the shortest path from the source to the destination. The packet then is forwarded along the shortest path greedily. Although this approach can alleviate the routing path enlargement problem, it fails to solve the problem of load imbalance (i.e., the nodes surrounding the vertices of the visibility graph are imposed heavier traffic than the others). In a previous work [11], we proposed a protocol for routing in the hole vicinity which can solve both the two problems. However, this protocol addresses only the simplest case where the network contains only one hole.

In this paper, we focus the routing problem in general cases where the network may contain multiple holes, and the sources/destinations may stay in the vicinity of the holes. We then propose a geographic routing protocol that can solve both the load imbalance and routing path enlargement problem. The contributions of our paper are as follows:

- We propose a distributed algorithm to determine the forbidden areas of the holes and a lightweight scheme to disseminate the hole information.
- We propose a geographic data forwarding algorithm that generates dynamic routing paths with the stretch upper bounded by a constant.
- We present an insightful analysis to prove the constant