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Published in:
Eurasip Journal on Wireless Communications and Networking

DOI:
10.1186/1687-1499-2014-66

Published: 01/01/2014

Document Version
Publisher's PDF, also known as Version of record

EURASIP Journal on Wireless Communications and Networking
a SpringerOpen Journal

RESEARCH **Open Access**

A reliable energy-balancing multi-group (REM) routing protocol for firefighter communication networks

Mahin K Atiq[1], Kamran Manzoor[2], Soomi Kim[3], Najam ul Hasan[1] and Hyung Seok Kim[1*]

Abstract

In a fire rescue operation, a fast, reliable, and robust communication system is needed to quickly take control of the emergent situation. One of the most important issues in firefighter communication networks (FCNs) is the design of a specialized routing protocol that caters to the specific needs of the fire rescue application. This paper proposes a reliable, energy-balancing, multi-group (REM) routing protocol for an FCN. Since firefighters work in groups, a cluster-based hierarchical approach was adopted. REM is intended to achieve reliability and energy balancing in data communication by incorporating metric-based cluster head (CH) selection, CH rotation among cluster members, and a routing algorithm. Within a cluster, the node with highest metric value based on residual energy and number of connections is chosen as the CH. The CH's responsibilities are rotated periodically among the cluster members. REM chooses nodes with a higher metric based on residual energy, number of connections, and number of hops to the base station (BS) as the next hop for forwarding data to the BS. This helps to achieve reliability, less delay, and energy balancing when compared with other routing schemes, as evident from the simulation results.

Keywords: Firefighter communication network; Energy-balancing; Multi-group

1 Introduction

One of the most essential public safety activities is fire rescue. Fire rescue operations are critical because the lives of rescue workers, firefighters, and of course civilians depend on them. A fire rescue operation starts with a fire alarm call, and a rescue operation team is sent to the fire field. Normally, the fire rescue team consists of one incident commander, fire rescue vehicles, and a set of firefighters organized in the form of groups, each led by a group leader. The fire rescue team is highly structured and organized. The incident commander is in charge of the whole fire rescue operation, including real-time tactical decision making for the firefighters and monitoring the fire field [1]. Fire rescue vehicles include a communication support equipment vehicle, that is, a base station (BS), which helps the incident commander and the firefighters to communicate with each other in the fire field; and a vehicle that carries water to be used if there is insufficient water at the fire field. Generally, firefighter groups are highly organized and have specified tasks assigned by the incident commander based on their geographical area or skills [2,3], for example, rescue, search, ladder operations, hose operations, pump operations, initial medical care, and so on. The basic aim of making firefighter groups is to rescue people while staying together at the fire field. No one should be left alone behind [4].

Recently, advanced fire rescue techniques have required sensing of environmental conditions and firefighters' vitals in addition to the regular command messages between the firefighters and the commander, who oversees the entire fire rescue operation [5]. The firefighter network usually consists of sensors either planted inside the firefighter uniform or deployed along the path [6]. The sensors continuously sense the environmental conditions and firefighters' vitals and send these updates to the BS. The firefighters move inside the fire field to find humans to rescue, as well as to extinguish the fire [7].

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The fire rescue operation has many shortcomings. First, the incident commander can neither have complete information about the current status of all the firefighters involved in the operation nor know the exact situation inside the fire field. Therefore, it becomes very difficult for the incident commander to make decisions with less available information. The firefighters themselves are also unaware of the dangerous situations ahead of them because fire situations are always different and unexpected [8]. Thus, the fire rescue operation requires the support of a communication network that can be easily established without any need for infrastructure to be installed [8,9].

High densities of smoke, higher temperatures, visibility down to zero, and all infrastructure covered with water impose several specific requirements for the firefighter communication network (FCN) [10]. Information about each firefighter, including his or her ID, name, age, specialties, group to which he or she currently belongs, location, heart rate, air tank pressure, blood pressure, and body temperature is needed to completely account for the firefighter in the fire field [4,11]. This information helps the incident commander keep track of all firefighters and initiate a rescue for the firefighter if he is lost or in critical state. Real-time information about firefighters' surrounding temperature, as well as the humidity, wind speed, and density of smoke is also required. This will help the incident commander to gain a full view of the fire field, allowing him or her to make better decisions and guide firefighters toward possible exits and safe locations [11]. The lives of the firefighters, rescue workers, and civilians depend on reliable and timely communication between the firefighters and the incident commander. Sensor data should be sent reliably and quickly to the incident commander so that he or she can make better decisions and help the firefighters in the fire field [11]. A typical firefighter network is presented in Figure 1.

Fire rescue operations have its own specific characteristics that impose many challenges on the firefighter communication protocol. An FCN is a pure *ad hoc* wireless network where the high mobility of firefighters and harsh environmental conditions impose strict requirements on the network to be self-organized. Due to harsh environment, links are broken frequently, so a good self-organizing protocol is needed to automatically reconfigure the network in a limited amount of time after a failure. To achieve self-organization in the firefighter communication protocol, several functions are highly desired, for example, the connections between the firefighters in a group and the BS should be established automatically; all the firefighters and BS in the FCN should be self-organized into an *ad hoc* wireless sensor network (WSN) in a short period of time; and the firefighters should maintain a connection along with their high mobility [9,11]. Reliable data delivery is another crucial requirement for an FCN. Therefore, in order to provide guaranteed data delivery, node failure-tolerant routing is highly desirable because this can cope with high mobility and node failure in order to avoid causing huge packet loss. The FCN consists of sensor nodes sensing the firefighters' vitals and environmental parameters. Sensor nodes are energy-constrained nodes and cannot be recharged during the rescue operation. Therefore, the FCN protocol should be designed with the energy constraint of the sensor nodes taken into consideration [11]. The real-time location of firefighters in the fire field is also crucial when it comes to helping and locating the firefighter in an emergency situation [4]. Furthermore, this information also helps the incident commander to get a clear view of the deployment of firefighters across the fire field. The rapid movement of firefighters in the fire field and mostly indoor rescue operations make the localization of firefighters a huge challenge. It is not feasible to use the global positioning system (GPS) for indoor localization because this would require line of sight with the GPS satellites. A novel localization algorithm is also needed to provide real-time location information to the firefighters [11].

One of the main issues with the FCN is the design of a routing protocol that addresses its special requirements. In this paper, we focus on this issue and propose a reliable, energy-balancing, multi-group (REM) routing protocol for FCN. The organization of firefighters in groups at the fire field motivates the use of a cluster-based approach. This approach helps to achieve self-organization and reduce the number of transmissions to longer distances, thereby saving energy as well. Each cluster has a cluster head (CH) that collects the data from cluster members. The collected sensor data is aggregated at the CH and forwarded to the BS; the incident commander uses this information to make tactical decisions. The CH responsibility is rotated among the cluster members for even distribution of energy consumption, thereby achieving energy balancing. The routing decisions are based on metrics such as the residual energy level of the nodes, number of hops to the BS, and number of connections (or one-hop neighboring CHs). To deliver data to the BS in multi-hop transmissions, choosing the forwarding nodes based upon the abovementioned metrics helps to achieve reliability, energy balancing, and low latency.

The rest of the paper is organized as follows: Related work is discussed in Section 2. Section 3 presents the system model for the proposed routing framework for FCN. The proposed routing protocol is presented in Section 4. Simulations and results are presented and discussed in Section 5. Conclusions are made in Section 6 of the paper.

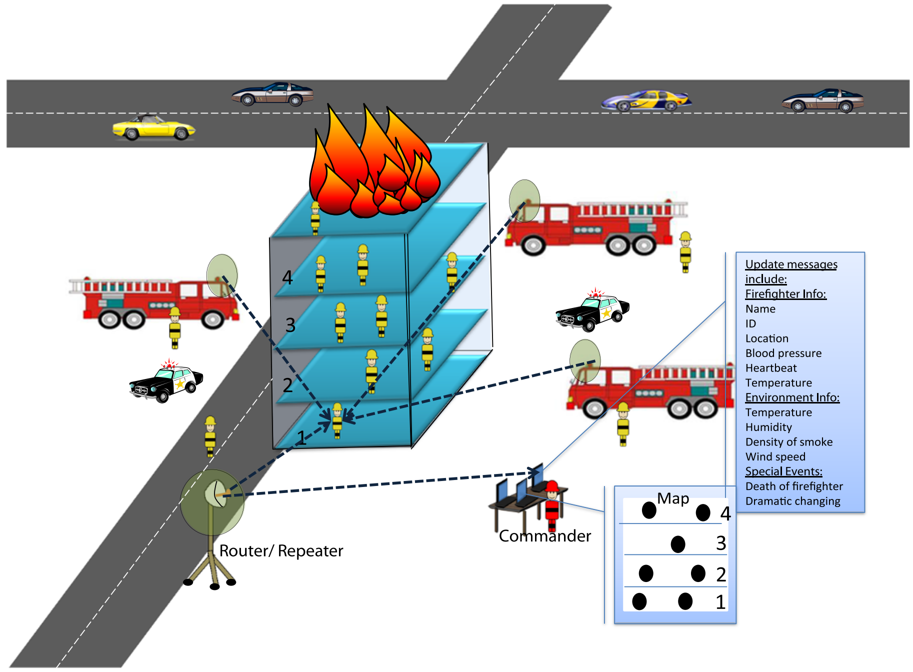

Figure 1 Firefighter communication network.

2 Related work

A lot of work on designing energy efficient routing algorithms can be found in WSNs or wireless *ad hoc* networks. However, no work has been conducted on designing a routing protocol for FCNs that can cater to their stringent requirements.

A low energy adaptive clustering hierarchy (LEACH) is presented in [12]. The algorithm rotates the CH's responsibility to conserve energy but requires the CH to transmit data to the sink in one-hop transmissions, resulting in great energy loss due to long-range transmissions. This causes CHs farther away from the sink to die out quickly compared to those closer to the sink. HEED, a hybrid clustering protocol presented in [13] uses a two-parameter communication cost factor to elect the CH. However, it requires complete information on all the nodes in the network to find the communication cost of the cluster members. It additionally suffers from the HotSpot problem - the nodes closer to the sink relay a disproportionately high amount of traffic information from the network to the sink and thus dies at a very early stage. In [14], Yu et al. presented a cluster-based routing scheme for WSNs. This proposed scheme includes a cluster-based routing algorithm along with an energy-aware distributed clustering (EADC) algorithm. The paper achieves load balance by forming clusters of the same size and forwarding data to nodes with higher energy and fewer one-hop neighbors. The scheme proposed in [14] has many drawbacks. The solution is presented for stationary nodes, and using nodes with fewer one-hop neighbors can decrease the reliability of the routing protocol. Additionally, the routing protocol does not consider the number of hops to the BS while making routing decision; this can induce serious delays and sometimes loops in the network. For the reasons mentioned above, this approach is not feasible for a firefighter network where the nodes are constantly mobile and delay can cause serious loss.

A novel cluster-based energy-efficient routing scheme for WSNs is presented in [15]. This paper proposes CH selection considering the energy and optimal CH distance-based CH selection and CH rotation among cluster members as a solution to resolving the energy consumption problem of WSNs. However, the scheme in [15] does not consider the number of one-hop neighbors as a criterion for the selection of a CH, and thus, reliability is reduced. An energy-efficient semi-static clustering scheme was proposed in [16] by Du et al. This was designed based on hierarchical agglomerative clustering (HAC) with energy-aware clustering. The CH rotation is carried out automatically using an ordered list and dynamic re-clustering is performed to achieve the even distribution of clusters. A drawback of this scheme is that CH rotation based on an automatic list can select a low-energy, inefficient node as the CH, causing data loss and delays. Civic and Aim presented a token-based, energy-efficient routing scheme for WSNs in [17]. The scheme employs cluster-based hierarchy with energy-based cluster formation and CH selection. The forwarding is carried out based on the residual energy of the node and distance from the sink. The location information is used to calculate the distance and multiple sinks are considered for data collection rather than a centralized sink or BS. The approach cannot be applied to the firefighter scenario, as achieving location information indoors in the fire site is very difficult and energy consuming. Moreover, the next hop selection procedure does not consider the one-hop neighbors or connections of a node, making the routing design unreliable for data delivery.

Considering the work done for emergency scenarios, especially in terms of firefighters, little research on firefighter networks can be found. In [18], Carli et al. presented a combined routing and localization scheme for emergency networks. The localization of nodes is incorporated in the cluster-based routing scheme to conserve energy consumption. The proposed scheme reduces the signaling information used for localization in prior studies, thereby reducing the energy consumption as well. However, the scheme is applicable to only the cases where a pre-deployed WSN is present and can be turned on in case of an emergency. In case of a fire, all infrastructures may be destroyed and the firefighters cannot rely on any pre-deployed infrastructure. Furthermore, the amount of time consumed in location calculation can cause serious delays for emergency response networks like FCNs. In [19], a lifeline support was provided for firefighters consisting of durable sensors. The proposed scheme helps to provide navigation support to firefighters in the fire field where visibility is highly impaired. However, the proposed scheme in [19], does not provide communication architecture for the FCN. Will et al. presented a prototype system for the emergency scenarios particularly fire field in [6]. This system monitors firefighters' vitals along with the environmental conditions using body-mounted sensors. The main problem with this proposed system is that it requires precise indoor localization and high delay is incurred in the localization.

In the approach proposed in this paper, an REM routing algorithm has been established for FCN. The proposed scheme incorporates a local sensor data collection at the CH and aggregation of this data at the CH before forwarding it to the next hop for BS. This approach helps to minimize transmissions over long distances, thereby saving energy. Keeping in mind the energy constraint and the reliable and timely message delivery requirements of the FCN, the proposed scheme uses the residual energy level, number of hops to the BS, and number of connections as a selection metric for the next hop to forward data to the BS. These selection criteria help in choosing more reliable routes and achieving energy balancing by distributing the transmission tasks among nodes. As shown in the results section, this scheme provides communication support to firefighters with the least delay, higher reliability, and longer network lifetimes compared to the other routing protocols.

3 System model

3.1 Network model

We consider a network model in which the firefighters work in groups at a fire scene. Each group is led by a group leader. Each firefighter group is assumed to be a cluster because fire rescue operations are inherently carried out by groups of firefighters working together cooperatively. Firefighters belonging to a single group are termed cluster members. Each cluster has a CH, which at the start of the fire rescue operation is the group leader. Another reason for using the hierarchical cluster network model is that it is most suitable for the firefighter network due to its rigorous energy constraints and because it helps to achieve self-organization and energy balancing among nodes. The hierarchical network model is shown in Figure 2. The network model operates as follows:

- The BS is out of the fire field, and assumed to have sufficient energy and processing power;
- The sensor nodes are embedded in the firefighter uniform;
- The CH collects sensor data from all cluster members. The collected sensor data is aggregated at the CH and forwarded to the BS using multi-hop transmission through one-hop neighboring CHs;
- Due to the sophisticated nature of the CHs' responsibilities, they require more energy. Therefore, the CHs' responsibility is rotated among cluster members to distribute the energy consumption evenly among all the cluster members;
- Each member node can transmit sensor data only to its own CH, hence conserves energy by reducing the number of transmissions to longer distances;

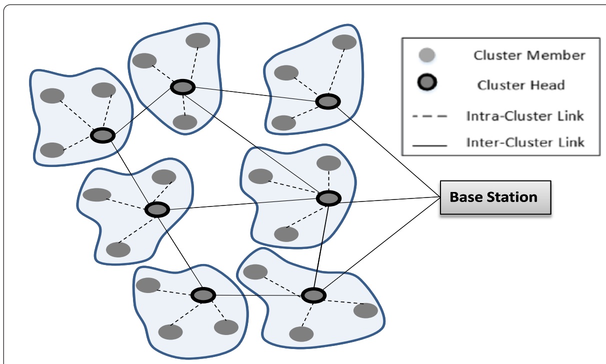

Figure 2 **Hierarchical cluster-based network model.**

- It is assumed that the cluster members are in close proximity and sense the same data that are aggregated at the CH;
- Only the CH needs to know how to forward the data to the next level CH or BS, so this reduces the complexity of the routing protocol.

3.2 Energy model

Energy consumption in a sensor network has the following four components depending on the type of operation performed by the sensor node:

1. *Sensing energy* (E_s): Energy consumed to activate the sensing circuitry of a node and collect data from the environment.
2. *Transmitter energy* (E_t): Energy consumed when the collected sensor data is transmitted to the destination. This depends upon the transmitter power, size of the data packet, and channel model.
3. *Receiver energy* (E_r): Energy used while receiving the sensor data from other nodes, which is independent of the distance between the communicating nodes.
4. *Computational energy* (E_c): To perform all the abovementioned operations, the sensor node processing unit also spends some energy; this is termed as computational energy.

As a summation of all the abovementioned components, the total energy consumption (E_{total}) is:

$$E_{\text{total}} = E_s + E_t + E_r + E_c. \tag{1}$$

E_s and E_c can be reduced using an efficient sensing circuitry and computational algorithm, whereas E_t and E_r depend on the communication architecture and underlying techniques. All of the components except E_t remain constant with the changing distance between the transmitter and receiver pair. In this paper, using the energy model presented in [12], we focus on E_t and E_r, which are given by Equation 2 and Equation 3, respectively, as follows:

$$E_t = \begin{cases} l \times E_{\text{elec}} + l \times \epsilon_{fs} \times d^2, & d < d_0 \\ l \times E_{\text{elec}} + l \times \epsilon_{mp} \times d^4, & d \geq d_0 \end{cases} \tag{2}$$

$$E_r = l \times E_{\text{elec}}, \tag{3}$$

where E_{elec}, ϵ_{fs} and ϵ_{mp} are transmission/reception circuitry-dependent parameters, l is the size of the message packet in bits, d is the distance between the communicating pair and d_0 is the threshold distance related to the node's hardware. Depending on the distance between the communication pairs, the free space (ϵ_{fs}) and multi-path fading (ϵ_{mp}) channel models may be used. In this paper, the multi-path channel fading model is employed.

Table 1 Description of messages

Messages	Description
Update_Msg	Includes {OwnId, OwnResidualEnergy, OwnConnections}
CH_Msg	Includes {OwnId}
Route_Msg	Includes {OwnId, OwnResidualEnergy, OwnConnections, OwnHopstoBS}
Data_Msg	Includes {Aggregated sensor data at the CH}

4 Proposed routing scheme

Based on the requirements and characteristics of the FCN, an REM routing protocol has been proposed. Each group of the firefighter rescue team is considered as a cluster. The proposed scheme consists of a CH selection algorithm and multi-group routing algorithm. The CH selection decision is attributable to the number of connections and residual energies of the competing nodes. The node with the highest value of the selection metric is selected as the CH. The selected CH leads the network in forwarding the sensor data from its member nodes to the BS, while simultaneously acting as a relay node for the other clusters. For this, a multi-group routing algorithm is designed. The next hop is selected among competing nodes based on the highest value of the selection metric consisting of the node's residual energy, number of hops to the BS, and number of connections. The proposed scheme can be divided into the following three key phases: CH selection, multi-group routing, and data transmission.

Table 2 Simulation parameters

Simulation parameters	Values
Sensor field	2,000 m × 2,000 m
Radio-propagation model	Two ray ground
Number of packets	1,000 packets
Size of packet	512 bytes
Packet generation rate	512 bytes/s
Radio type	802.11b
MAC protocol	802.11
Mobility model	Random waypoint group
Nodes' average speed	1 to 5 m/s
Initial energy of nodes	1 J
E_{elec}	50 nJ/bit
ϵ_{mp}	0.0013 pJ/bit/m^4
Simulation time	7,000 s

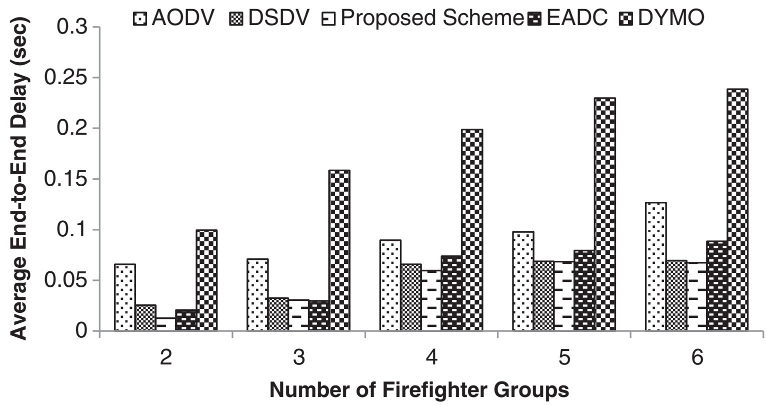

Figure 3 Average end-to-end delay for five schemes with an increasing number of firefighter groups.

The messages exchanged in this process are provided in Table 1.

4.1 Cluster head selection

The clusters are formed inherently because each firefighter group is considered a cluster. Initially, each group leader is chosen as the CH. Each node has entries in its routing table to identify its group and group members. Each node i broadcasts periodic Update_Msg containing its own ID, residual energy ($E_{\text{res}}(i)$), and number of connections ($C(i)$). $E_{\text{res}}(i)$ defines the state of node i in terms of energy and the higher energy nodes help to minimize link breakage by avoiding node failure. $C(i)$ defines the alternate routes, and when channel conditions become worse and mobility is high, a higher value of $C(i)$ is desired. Higher values of C and E_{res} help to achieve reliability. Meanwhile, each node also receives a periodic Update_Msg from the member nodes j at regular intervals and updates its routing table. Once the shortest path is achieved, that is, when the routing table is said to be matured, each node i calculates the value of CH selection variable (CH_{select}) using (4) for itself and its member nodes:

$$\text{CH}_{\text{select}}(i) = \zeta \cdot E_{\text{res}}(i) + \kappa \cdot C(i), \tag{4}$$

where ζ and κ are positive integers, whose values depend on the requirements of the FCN. Each node then compares the value of $\text{CH}_{\text{select}}(j)$ for member nodes to its own $\text{CH}_{\text{select}}(i)$. If the node itself has the highest value of $\text{CH}_{\text{select}}$, it broadcasts CH_Msg to advertise that it is the new CH. Each node receiving CH_Msg updates its routing table for the new CH. Otherwise, it waits to receive CH_Msg from the other member nodes. If node i has same value $\text{CH}_{\text{select}}$ as any other member node j, then the CH selection is carried out based on Node_ID comparison, where the node with the highest ID is selected as the new CH. Each node receiving the CH_Msg updates its routing table for the new CH. The CH selection procedure is repeated periodically after every $t = T_1$ seconds to achieve energy balancing among the member nodes. The pseudo-code for the CH selection algorithm is given below.

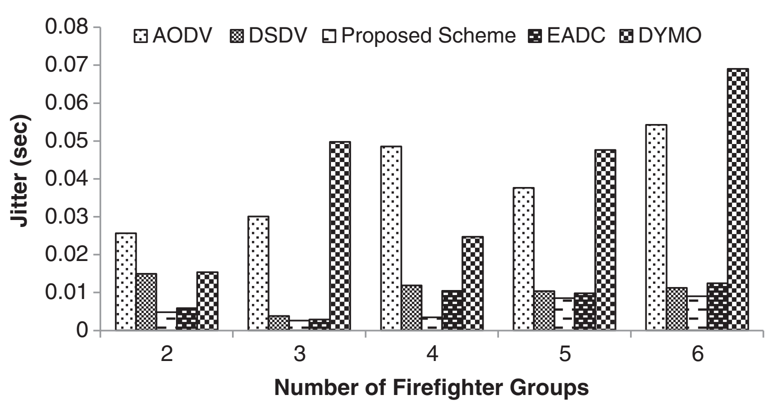

Figure 4 Jitter for five schemes with an increasing number of firefighter groups.

Begin (CH selection algorithm)
  for each node i
    ⋆ After every T_1 seconds
    ⋆ Send Update_Msg
    ⋆ Receive Update_Msg from member nodes
    ⋆ Update routing table
    if (routing table of node i is matured)
      ⋆ Calculate $\text{CH}_{\text{select}}$ for each member node j in the routing table and itself
      if ($\text{CH}_{\text{select}}(i) > \text{CH}_{\text{select}}(j)$) $\forall\, j, j \neq i$
        ⋆ Broadcast CH_Msg
        ⋆ Update CH = node i
      else if ($\text{CH}_{\text{select}}(i) == \text{CH}_{\text{select}}(j)$) $\forall\, j, j \neq i$
        if (Node_ID(i) > Node_ID(j))
          ⋆ Broadcast CH_Msg
          ⋆ Update CH = node i
        end
      else
        ⋆ Receive CH_Msg from member node j
        ⋆ Update CH = node j
      end
    end
  end

4.2 Multi-group routing

In the proposed multi-group routing scheme, where each node is considered a cluster member, nodes construct a routing tree based upon the CH designated in the CH selection phase. The nodes use a multi-hop forwarding scheme to send sensor data to the BS to further reduce the energy consumption and achieve energy balancing.

Each member node forwards the data packets to its own CH. Each CH m broadcasts Route_Msg consisting of its own ID, residual energy ($E_{\text{res}}(m)$), number of connections ($C(m)$) and number of hops to BS ($H(m)$), after every $t = T_2$ seconds. The importance of $E_{\text{res}}(m)$ and $C(m)$ have been discussed earlier. $H(m)$ defines the amount of time taken for each packet to reach the BS. A higher value of $H(m)$ indicates a path with higher delay. Each CH also periodically receives Route_Msg from neighboring CHs and updates the routing table. Based on the received Route_Msg, node m computes the value of next hop selection variable ($\text{NH}_{\text{select}}$) for the neighboring CHs m using:

$$\text{NH}_{\text{select}}(j) = \alpha \cdot E_{\text{res}}(j) + \beta \cdot (H(j))^{-1} + \gamma \cdot C(j), \quad (5)$$

where α, β, and γ are positive integers, whose values depend on the requirements of the FCN. The CH n with highest value of $\text{NH}_{\text{select}}$ is selected as the next hop to the BS. If two CHs have the same value of $\text{NH}_{\text{select}}$, then the node with highest Node_ID is selected as the next hop to the BS. The multi-group routing algorithm is explained in the pseudo code below.

Begin (Multi-group routing algorithm)
  for each node n
    if (Node $\neq$ CH)
      ⋆ Update NextHop = OwnCH
    else
      ⋆ After every T_2 seconds
      ⋆ Send Route_Msg
      ⋆ Receive Route_Msg
      ⋆ Update routing table
      ⋆ Compute $\text{NH}_{\text{select}}$
      ⋆ Compare $\text{NH}_{\text{select}}$ for all the neighbor CHs n
      for all neighbor CHs n
        if $\text{NH}_{\text{select}}(n) > \text{NH}_{\text{select}}(k)$ $\forall$ k = 1,2,3,...,n, $n \neq k$
          ⋆ Update NextHop = CH n
        else if ($\text{NH}_{\text{select}}(n) == \text{NH}_{\text{select}}(k)$)
          if (Node_ID(n) > Node_ID(k))
            ⋆ Update NextHop = CH n
          end
        end
      end
    end
  end

The variables E_{res}, H and C used in (4) and (5), are normalized using a unity-based normalization method, as shown below:

$$X_{n\ (0\text{ to }1)} = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}}, \quad (6)$$

where X_n, X_i, $X_{\max}$ and $X_{\min}$ are the normalized, ith, maximum, and minimum values of the variable X, respectively. The normalizations are carried to bring all three variables into the same data range so that the weights assigned can be formulated accordingly.

4.3 Data transmission

The process of data transmission to the BS can be divided into the following two phases: intra-cluster communication and inter-cluster communication. In intra-cluster communication, each cluster member collects data from the sensors embedded in the firefighter's uniform and forwards them to the CH. Each cluster member is just one

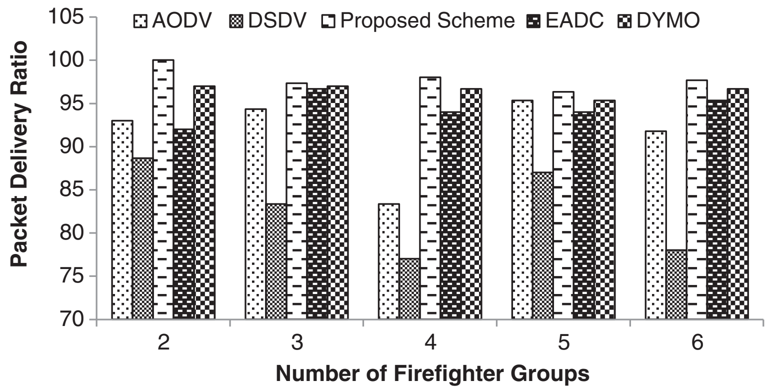

Figure 5 Packet delivery ratios for five schemes with an increasing number of firefighter groups.

hop away from the CH as in LEACH [12]. The CH aggregates the data received from member nodes, into one Data_Msg, which is forwarded to the BS. Each CH uses a multi-hop forwarding mechanism, constructing a path that involves other CHs as intermediate nodes to the BS. This multi-hop forwarding mechanism helps to further reduce the energy consumption by reducing transmissions over longer distances.

5 Simulation and results

Extensive simulations were conducted on QualNet 5.0 to evaluate the performance of the proposed REM routing scheme. The aim of the simulations was to study the effect of (a) number of groups, (b) number of firefighters per group, and (c) mobility on the REM, in comparison with the AODV, DSDV, DYMO, and EADC. The EADC routing protocol presented by Yu et al. in [14] includes an energy-aware clustering algorithm and a cluster-based routing algorithm. The EADC chooses the node with higher energy as the CH. It then uses the CHs with higher residual energy and a fewer number of connections as relay nodes to the BS. We used the DSDV, AODV, and DYMO implementations available in the QualNet 5.0 library and implemented the EADC and the proposed REM routing protocols in QualNet 5.0 to obtain comparisons. The two-ray ground path loss model was used for the simulation. Here, one group is chosen as the source of sensor traffic and constant bit rate (CBR) traffic is used for transmissions from the nodes to the BS. The source node generates 1 packet per second, 1,000 packets in total, and each carrying 512 bytes of data. The complete set of simulation parameters is listed in Table 2.

We used the following performance metrics for evaluation of the schemes:

- *Average end-to-end delay* → The average time taken to traverse the network, expressed in seconds. This is the time starting from the packet generation at the source to the application layer of the sink. Average end-to-end delay includes all the network delays, that is, the delays by MAC control exchanges, routing activities, buffer queues, and transmission time [20].
- *Jitter* → The difference between arrival times of packets at the receiver, expressed in seconds. Jitter is caused by changes in network congestion, route queuing, or discovery [21].

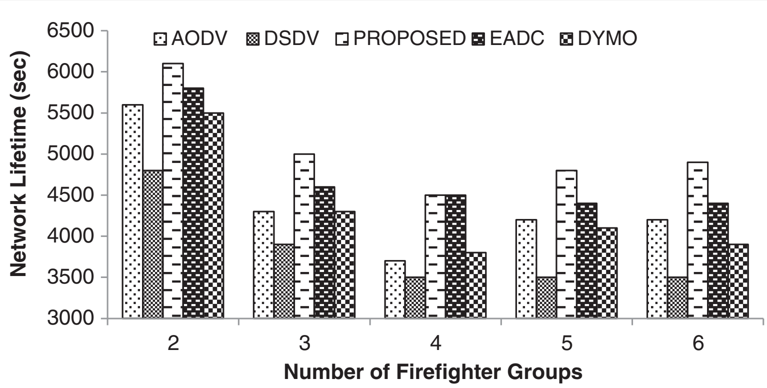

Figure 6 Network lifetime for five schemes with an increasing number of firefighter groups.

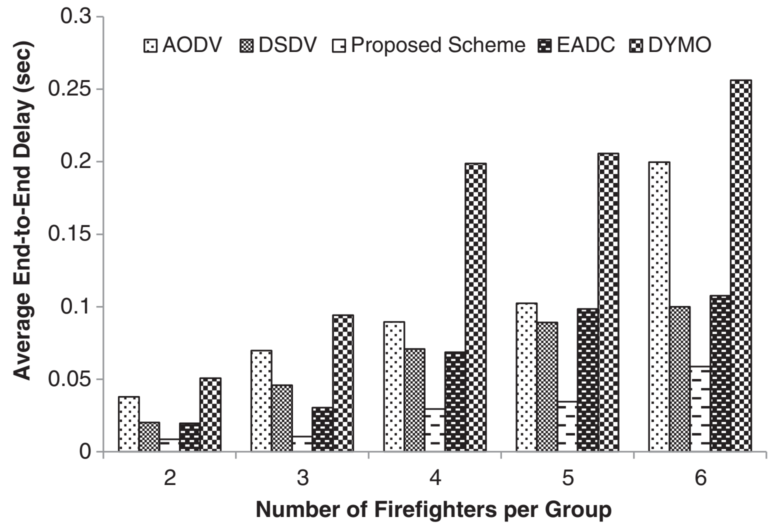

Figure 7 **Average end-to-end delay for five schemes with increasing number of firefighters per group.**

- *Packet delivery ratio (PDR)* → The ratio of the total number of packets received at the CBR sink to the total number of packets generated at the application layer of the CBR sources [22].
- *Network lifetime* → According to the definition given in [23], there are three kinds of metrics to define the network lifetime: (a) the time from the deployment of the network to the death of the first node, namely first node dead (FND); (b) the time from the deployment of the network to the death of all nodes in the network, namely last node dead (LND) and (c) the time when a certain percentage of nodes is alive, namely percentage node alive (PNA). In this paper, the network lifetime is considered as the first node dead time (FND).

5.1 Effect of number of firefighter groups

To study the effect of the number of firefighter groups at the fire field on the REM, AODV, DSDV, DYMO, and EADC, we varied the number of groups from 2 to 6 with four firefighters in each group. The minimum speed of the firefighters is 1 m/s, with a pause time of 10 s following a random waypoint group mobility model, as presented in [24].

Figure 3 shows the effect of number of firefighter groups on the five protocols. As the number of firefighter groups increases, the delay also increases for all the schemes because of packet queuing delays and the increasing distance from the BS. The proposed REM outperforms all the other protocols because it includes the number of hops as a decision metric for choosing nodes to forward the data. Higher energy nodes are more reliable. This causes lesser link failures, and consequently lesser number of tires in finding new paths. DYMO has the highest delay due to the congestion problem arising due to large number of control packets exchanged. As the number of firefighter groups increases, the delay increases significantly for DYMO.

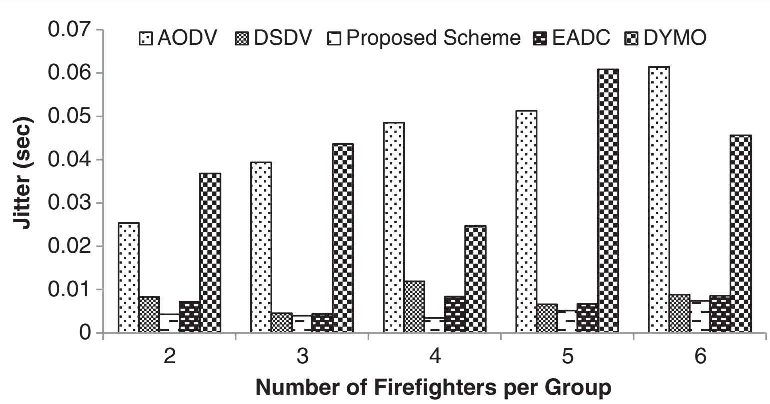

Figure 8 **Jitter for five schemes with increasing number of firefighters per group.**

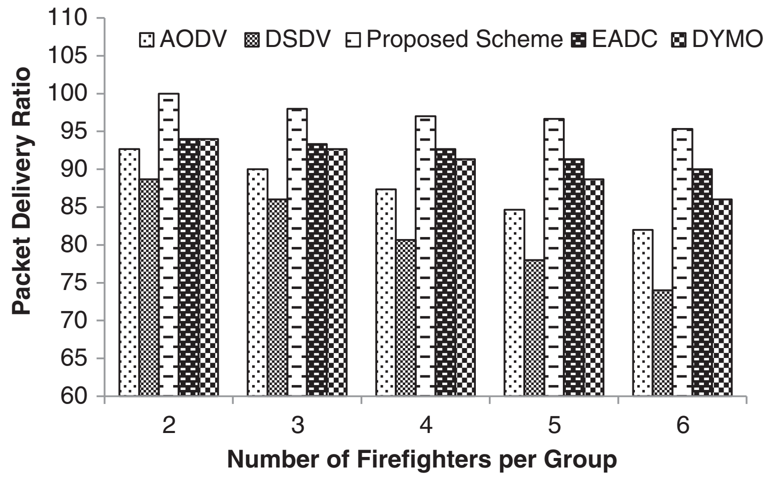

Figure 9 **Packet delivery ratio for five schemes with increasing number of firefighters per group.**

Figure 4 compares the jitter for five schemes with an increasing number of firefighter groups. REM outperforms all other schemes in the jitter comparison and faces the least route failures because of more energy-efficient routes, while route request packets flooding into the network, as occurs in the AODV and DYMO, causes higher inter-packet delay.

The PDRs of five schemes are compared in Figure 5. The REM has the highest PDR among the schemes and remains almost constant as the number of firefighter groups increases. This occurs because the nodes chosen as CH and the relay nodes for data forwarding to the BS are higher energy nodes and have more connections. Therefore, they provide a more reliable path for data forwarding as compared to the other schemes. The DSDV has the lowest PDR because it performs worst in the presence of mobility.

The lifetimes of the networks among the five schemes are compared in Figure 6 among five schemes. The REM performs the best because it rotates the CH responsibility among the member nodes and creates a balance in energy consumption of the member nodes. The REM also uses nodes with higher energy for forwarding the data. This helps to distribute the energy consumption among different nodes in the network, avoiding the problem of just a few nodes being burdened with the responsibility of forwarding the data to the BS (which would cause them to die quickly), thereby achieving energy balancing. In the case of the DSDV, the nodes die very quickly due to the regular updating of the routing table (exchanging complete routing tables consumes a lot of energy).

5.2 Effect of number of firefighters per group

The number of firefighters per group varied from two to six. The total number of groups in the network simulation was set to 6. The minimum speed of the firefighters was 1 m/s, with a pause time of 10 s following a random waypoint group mobility model as presented in [25]. Here, the

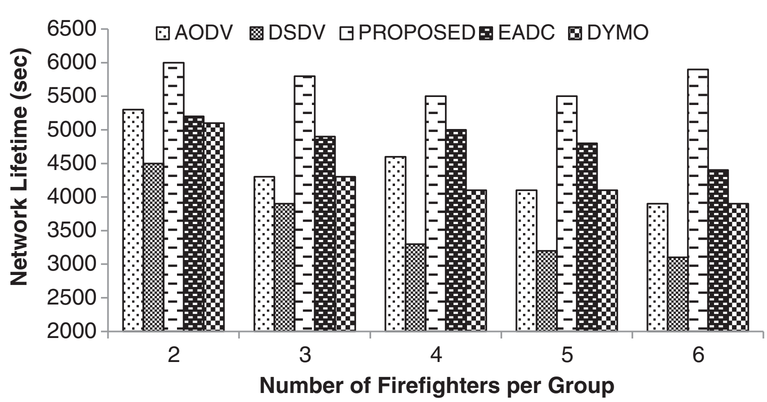

Figure 10 **Network lifetime for five schemes with increasing number of firefighters per group.**

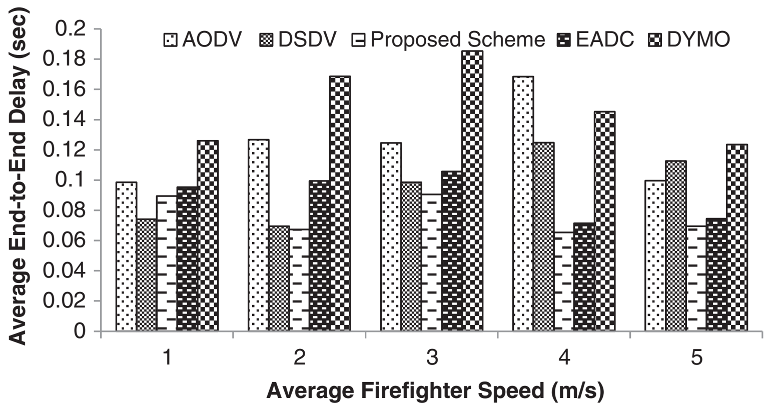

Figure 11 Average end-to-end delay for five schemes with increasing firefighter speed.

CBR traffic is delivered from one of the groups and to the BS and the simulation results are compared.

The average end-to-end delay for the five schemes is compared in Figure 7. As the number of firefighters per group increases, the delay also increases for all schemes. The delay increases significantly in the AODV and DYMO schemes because of their on-demand route-finding characteristics. The REM exhibits less delay than other existing schemes and the variation is minimal even when the number of firefighters per scheme is varied. This occurs because of the data aggregation at the CH and the next hop selection metric, including the number of hops to the BS. The EADC also aggregates the sensor data at the CH before forwarding to the BS, but uses nodes with fewer connections and does not include the number of hops when selecting nodes as relay nodes. This causes a greater delay than in the REM.

Jitter for the AODV, DSDV, DYMO, EADC, and REM is compared in Figure 8. Due to the data aggregation at the CH and the fewer hops to reach the BS, the proposed scheme outperforms the others. The AODV and DYMO are on-demand routing protocols, and as the number of sources increases with the increasing number of firefighters per group, this causes more link failures and more route discoveries, resulting in high jitter.

Figure 9 shows the effect on PDR of increasing the number of firefighters per group. As the number of firefighters per group increases, the PDRs for the AODV, DSDV, and DYMO decrease, whereas in the REM and EADC, the PDR remains almost constant. The aggregation of data at the CH in the proposed scheme and the EADC helps to reduce the number of packets in the network. However, the REM forwards the data using nodes closer to the BS and has more alternate routes, avoiding node failure by using higher energy nodes; thus, delivery packets are more reliable in this scheme than in any other under comparison.

Figure 10 compares the network lifetimes for the five schemes with an increasing number of firefighters per group. In the cases of the AODV, DSDV, and DYMO, the network lifetime decreases with an increasing number of firefighters per group. This is because as the number of

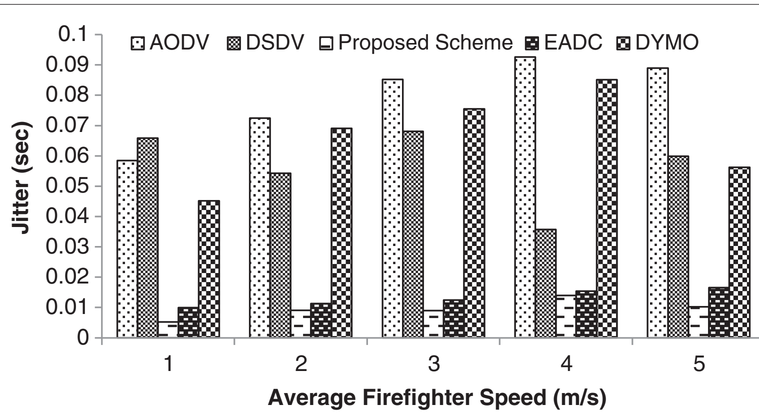

Figure 12 Jitter for five schemes with increasing firefighter speed.

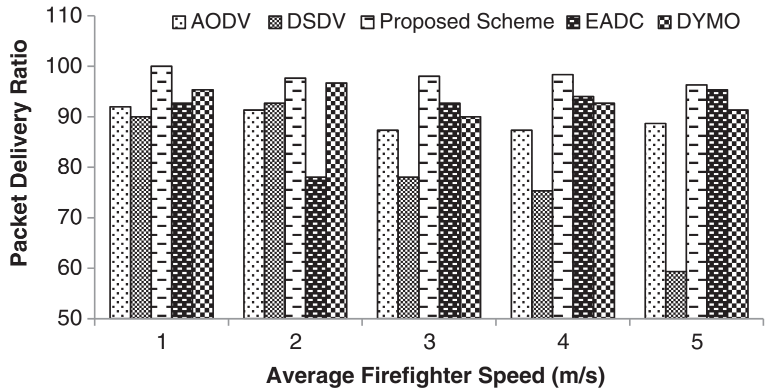

Figure 13 **Packet delivery ratio for five schemes with increasing firefighter speed.**

firefighter increases, the number of sources also increases, and more packets are exchanged in the network, thereby causing the network lifetime to decrease. However, in the cases of the EADC and REM, the data aggregation helps to decrease the number of packets sent from a source to a destination, and thus they do not show a significant decrease. In the case of the REM, more alternate routes are present because nodes with more connections are used for forwarding data, which helps to reduce the energy consumption and distribute the energy among nodes more evenly in comparison with the other schemes. The rotation of CH responsibilities among the member nodes also helps to achieve energy balancing.

5.3 Effect of mobility

To study the effect of mobility on the five schemes, the network was simulated using six firefighter groups, with each group consisting of four firefighters. The CBR traffic is connected between the firefighters in one group and the BS. The average minimum speed of the firefighters is varied from 1 to 5 m/s, keeping in mind the average speeds of firefighters working in the fire field given in [4]. The mobility model used is the random waypoint group mobility model presented in [24] and implemented in the QualNet 5.0 wireless library.

The average end-to-end delay with increasing firefighter speed is compared in Figure 11. The REM performs the best among the schemes compared. The inclusion of number of hops to the BS as a selection metric for the next hop helps to reduce the delay; furthermore, the REM uses nodes with more connections and energy as CH and forwarding nodes in order to achieve reliability, thereby avoiding link failures and new path retries. Even when the speed increases, this does not greatly affect the REM. In the case of the AODV and DYMO, which are on-demand routing protocols, increasing speed causes more route requests in the network, resulting in congestion and higher delays.

Figure 12 gives a comparison of jitter in the five schemes with increasing firefighter speed. In the case of AODV and DYMO, the on-demand route requests and route replies cause high jitter. The DSDV routing protocol has a high jitter because of the high signaling traffic in the case of high mobility. The REM outperforms all the other

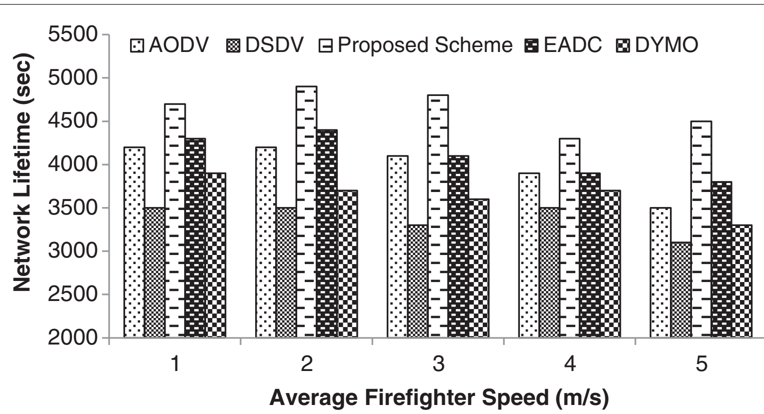

Figure 14 **Network lifetime for five schemes with increasing firefighter speed.**

schemes due to the use of nodes with more alternative routes to cater for the mobility problem.

The REM has the highest PDR when compared to the other schemes as the firefighter speed increases, as shown in Figure 13. It uses residual energy level, number of connections, and hops to the BS as the next hop selection metrics to select nodes as relay nodes for forwarding data to the BS. The PDR for the REM remains close to 100%.

Figure 14 compares the network lifetime of all five schemes. As the firefighter speed increases, the network lifetime decreases for all the schemes because of the greater exchange of control messages. The REM outperforms the rest of the schemes because of its ability to distribute energy consumption and avoid link failures, thereby avoiding retransmissions. The DSDV performed the worst because of the high number of retransmissions and higher signaling traffic. In the case of the EADC, because the node chooses CHs with fewer connections as relay nodes to the BS, this causes higher delay and packet drops, resulting in decreased network lifetime in comparison to the REM.

6 Conclusion

In this paper, a reliable, energy-balancing, multi-group (REM) routing protocol was proposed to cater to the specialized needs of firefighter communication networks (FCNs). The proposed scheme included a cluster head (CH) selection metric, a CH rotation procedure, and a routing protocol to provide a reliable and energy-balancing solution to the routing problems in FCNs. The REM scheme uses a metric value based on the residual energy and number of one-hop neighbors or connections of a node for CH selection. This helps to select nodes with higher energy and more alternative routes as CHs, thereby achieving reliability. The energy balancing among the nodes was achieved by incorporating a CH rotation function and an energy-balancing routing scheme. The proposed REM routing protocol helps to achieve reliability and energy balancing by distributing the traffic load among nodes based upon their residual energy, number of hops to the base station (BS), and number of connections. To evaluate the performance of the REM routing scheme and to compare its performance against the AODV, DSDV, DYMO, and EADC, extensive simulations were conducted. The simulation results showed that the proposed scheme is able to outperform all the others in terms of average end-to-end delay, jitter, packet delivery ratio (PDR), and network lifetime.

Competing interests

The authors declare that they have no competing interests.

Acknowledgements

This work was supported by the CITRC (Convergence Information Technology Research Center) support program (NIPA-2013-H0401-13-1003) supervised by the NIPA (National IT Industry Promotion Agency) of the MKE (Ministry of Knowledge Economy) Special Disaster Emergency R&D Program from National Emergency Management Agency (2012-NEMA10-002-01010001-2012).

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Received: 16 December 2013 Accepted: 25 March 2014
Published: 23 April 2014

References

1. MK Atiq, HS Kim, K Manzoor, Cluster based routing protocol for public safety networks, in *the Proceedings of the International Conference on ICT Convergence (ICTC)* (IEEE Jeju Island, 2013), pp. 435–439
2. T Doumi, MF Dolan, S Tatesh, A Casai, G Tsirtsis, K Anchan, D Flore, LTE for public safety networks. IEEE Commun. Mag. **51**(2), 106–112 (2013)
3. AM Naghsh, J Gancet, A Tanoto, C Roast, Analysis and design of human-robot swarm interaction in firefighting, in *Proceedings of the 17th IEEE International Symposium on Robot and Human Interactive Communication* (IEEE, 2008), pp. 255–260
4. IFTSA committee, *Essentials of Firefighting and Fire Department Operations, ed. 5*. (Fire protection Publications, Stillwater, 2008)
5. C An, A Timm-Giel, C Goerg, Virtual sensor network lifeline for communications in fire fighting rescue scenarios, in *Proceedings of the IEEE 70th Vehicular Technology Conference Fall* (IEEE, 2009), pp. 1–5
6. H Will, T Hilebrandt, M Kyas, Wireless sensor networks in emergency scenarios: the Feuerwhere deployment, in *Proceedings of the Sensor-Enhanced Safety and Security in Public Spaces* (South Carolina, USA, 2012), pp. 9–13
7. M Klann, Playing with fire: user-centered design of wearable computing for emergency response, in *Mobile Response* (Springer Berlin Heidelberg, 2007), pp. 116–125
8. A Timm-Giel, K Kuladinithi, P Hofmann, C Gorg, Wireless and ad hoc communications supporting the firefighter, in *Proceedings of the 15th IST Mobile Summit* (Mykonos, Greece, 2006)
9. F Theoleyre, F Valois, A self-organization structure for hybrid networks. Ad-hoc Netw. **6**(3), 393–407 (2008)
10. Y Chen, D Li, C Wang, J Wang, MFDSSF: A Mobile Fuzzy Decision Support System for Firefighter cooperation in ad hoc networks, in *Proceedings of the IFIP International Conference on Network and Parallel Computing* (IEEE, 2008), pp. 475–482
11. K Sha, W Shi, O Watkins, Using wireless sensor networks for fire rescue applications: requirements and challenges, in *Proceedings of the International Conference on Emerging Technology* (IEEE Piscataway, 2006), pp. 239–255
12. WR Heinzelman, A Chandrakasan, H Balakrihnan, Energy efficient communication protocol for wireless microsensor networks, in *Proceedings of the 33rd Annual Hawaii IEEE International Conference on System Sciences* (IEEE Piscataway, 2000), pp. 4–7
13. O Younis, S Fahmy, HEED: a hybrid, energy-efficient, distributed clustering approach for ad-hoc sensor networks. IEEE Trans. Mobile Comput. **3**(4), 366–379 (2004)
14. J Yu, Y Qi, G Wang, X Gu, A cluster based routing protocol for wireless sensor networks with non-uniform node distribution. Int. J. Electron. Comm. **66**(1), 54–61 (2012)
15. ASK Mammu, A Sharma, U Hernadez-jayo, N Sainz, A novel cluster based energy efficient routing in wireless sensor networks, in *Proceedings of the IEEE International Conference on Advance Information Networking and Applications* (IEEE Piscataway, 2013), pp. 41–47
16. T Du, S Qu, F Liu, Q Wang, An energy efficient semi-static routing routing algorithm for WSN based on HAC clustering method. Inform. Fusion. **14**(3) (2013)
17. T Cevik, AH Zaim, EETBR: Energy efficient token based routing for wireless sensor networks. Turk. J. Electr. Eng. Comput. Sci. **21**, 513–526 (2013)
18. M Carli, S Panzieri, F Pascucci, A joint routing and localization algorithm for emergency scenario. Ad Hoc Networks. **13**, 19–33 (2014)
19. HA Salam, SR Rizvi, S Ainsworth, S Olariu, A durable sensor enabled lifeline support for firefighters, in *Proceedings of the IEEE INFOCOM Workshops* (IEEE Piscataway, 2008), pp. 1–6

20. M Bansal, R Rajput, G Gupta, Mobile ad hoc networking (MANET): routing protocol performance issues and evaluation considerations. *Mobile Ad-hoc Network (MANET) Working Group, IETF* (RFC Editor, Fremont, 1998)
21. MM Morshed, MH Rahman, MRR Mazumder, K Lutfullah, Simulation and analysis of ad-hoc on-demand distance vector routing protocol, in *Proceedings of the International Conference on Interaction Sciences: Information Technology, Culture and Human* (ACM New York, 2009), pp. 610–614
22. L Tamilselvan, V Sankaranarayanan, Prevention of blackhole attack in MANET, in *Proceedings of the 2nd International Conference on Wireless Broadband and Ultra Wideband Communications, AusWireless* (IEEE Piscataway, 2007), pp. 21–21
23. S Gamwarige, E Kulasekere, An algorithm for energy driven cluster head rotation in a distributed wireless sensor network, in *Proceedings of the International Conference on Information and Automation* (Colombo, Sri Lanka, 2005), pp. 354–359
24. X Hong, M Gerla, G Pei, C-C Chiang, *A group mobility model for ad-hoc wireless networks* (ACM, New York, 1999), pp. 53–60
25. T Camp, J Boleng, V Davies, A survey of mobility models for ad hoc network research. Wireless Communications and Mobile Computing. **2**, 483–502 (2002)

doi:10.1186/1687-1499-2014-66
Cite this article as: Atiq *et al.*: A reliable energy-balancing multi-group (REM) routing protocol for firefighter communication networks. *EURASIP Journal on Wireless Communications and Networking* 2014 **2014**:66.