Energy-Efficient TDMA Dynamic Cluster Protocol for Ad Hoc Wireless Networks

Dali Wei, *Member, IEEE,* and H Anthony Chan, *SrMember, IEEE*

***Abstract*—Self-configuring Ad hoc wireless network is characterized by dynamic topology and limited energy supply. Energy efficiency of the network is an important issue. In Cluster algorithm, nodes are separated into groups, with one clusterhead in each group. Data are collected by the clusterhead in each cluster and energy is saved by reducing re-transmission data. However, there are still some drawbacks to existing cluster schemes. In this paper, we propose a new protocol called TDMA Dynamic Cluster (TDC), which improves the existing cluster algorithm. In our design, clusterheads are set at the center of each cluster at any time. By limiting the transmission range of the clusterhead, we solve the problem of overlap. TDMA is applied to elect clusterheads in designated time slots to average out the power consumption of each node. Directional route and free collision schemes are designed to avoid duplicated transmission of data through multiple routes. By these ways, the lifespan of the whole network can be prolonged.**

***Index Terms*—Ad Hoc, Energy efficiency, TDMA Dynamic Cluster, Wireless.**

I. Introduction

A. Ad Hoc Wireless Network

AD-HOC Wireless Network is a self-organizing multihop system of nodes without pre-existing infrastructure, and is characterized by dynamic topology and limited energy supply. The nodes can communicate with each other: each can act as a router to relay packets to its neighbors.

Because the energy sources of the nodes used in the ad hoc wireless networks are limited and are usually un-rechargeable, more and more attention today is being paid to energy efficiency, especially in sensor networks. An energy efficient design will prolong the lifespan of the network.

In this paper, we propose an energy efficient scheme based on a dynamic clustering protocol.

Manuscript received 3 May, 2005. This work was supported in part by Telkom, Siemens and National Research Council, South Africa under the Broadband Communication Center of Excellence Program.

Dali Wei is PhD student at Department of Electrical Engineering, University of Cape Town, Private Bag, Rondebosch 7701, South Africa. (e-mail: dlwei@crg.ee.uct.ac.za).

H. Anthony Chan is professor at the Department of Electrical Engineering, University of Cape Town, Private Bag, Rondebosch 7701, South Africa (e-mail: h.a.chan@ieee.org).

B. Cluster Protocol

With a cluster protocol, the nodes in the ad hoc network are separated into groups called clusters. In each cluster, one node is elected as the clusterhead to act as a local controller, while the rest are normal nodes. The size of the cluster is determined by the transmission power of the clusterhead.

As shown in Figure 1, the normal nodes in each cluster send data to their clusterhead. The clusterheads act as routers to form the backbone of the network. The collected data are then routed by these clusterheads to the data sink (which is also called base station) for further analysis.

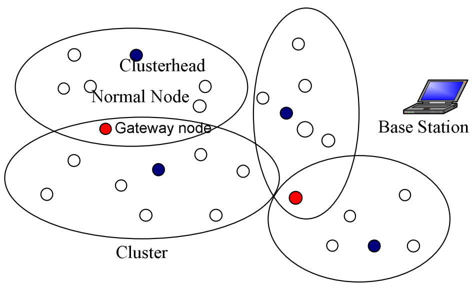

Fig. 1. Cluster Protocol.

The cluster protocol has many advantages, such as the following [1, 2]:

1) Within a cluster, all the normal nodes send their data to the clusterhead. The resulting absence of flooding protocol, multiple routes, or routing loops result in energy saving.
2) The backbone network consists of the clusterheads only. Because there are far fewer clusterheads than the total number of nodes in the entire network. Routing with the backbone network is therefore simpler, and requires less storage of routing information and less overhead of the ad hoc network.
3) The changes of nodes within a cluster affect only that cluster but not the entire backbone network, which will therefore be robust to these changes.

Many cluster protocols have been proposed (Section 2) but there are some common drawbacks (Section 3). To overcome these drawbacks, a new design called TDC is proposed (Section 4). Further improvements over TDC are possible (Section 5).

II. Related Work

A lot of research about cluster route and power consumption have been conducted in the field of Ad Hoc wireless networks. We summarize 17 of them and classified 10 into the following three categories: Cluster size optimization schemes, averaging power consumption schemes, CDMA and TDMA schemes. The remaining are other protocol schemes.

A. *Cluster size optimization schemes*

The size of the cluster is an important paramter. If the cluster size is decreased, the power consumption within each cluster is smaller. Yet the number of clusterheads will then be increased, so that the resulting backbone network formed by these clusterheads will become more complicated. A smaller number of clusterheads will form a simpler backbone network. Yet that would require larger cluster size, so that the RF power in each cluster becomes higher. There is then a tradeoff between the cluster size and the number of clusterheads. Several schemes have been proposed to achieve power efficiency by optimizing the cluster size [1-4]:

The distributed randomized algorithm proposed by Lakshmi et. al. [3] uses star-shaped clusters and finds the minimum number of such clusters which have the maximum size. The clusterheads are autonomously elected by the nodes.

Kai Liu et. al. [2] uses a mobile cluster algorithm and strategy to optimize the cluster size by overlapping clusters which can increase the maximum capacity of every node and the end-to-end throughput of the whole network.

Imrich et. al. [1] propose to determine the optimal assignment of nodes to clusterheads, which maximize the network lifetime.. C.F. Chiasserini et. al. [4] also determine the optimal cluster size and optimal assignment of nodes to clusterheads to maximize the lifetime of the network. However, knowledge of the number and the location of the clusterheads are assumed. In addition, the nodes needs to know the complete topology of the network.

B. *Averaging power consumption schemes*

Because the CHs are transfering data they gather from the normal nodes, they will run out of energy faster than normal nodes and the clusters will then break down. To prolong the lifespan of the network, different schemes to rotate the CHs and to average the power consumption in the cluster (not in the whole network) have been proposed [5-8].

One may use a power aware routing protocol by Toh [5], which combine the two constraints of evenly distruting the power consumption, and minimizing the overall transmission power of each connection. Another way is to use a centralized routing protocol is to distribute the energy dissipation evenly among all nodes, as in Base-Station Controlled Dynamic Clustering Protocol (BCDCP) by Muruganathan [6].

The clusterheads may be rotated randomly to average the power consumption of each node, as in the Lower-Energy Adaptive Clustering Hierarchy (LEACH) is proposed by W. R. Heinzelman et al [7].

In the re-clustering redirection scheme by Liu et al [8]. traffic loads are evenly distributed by selecting, at different cycles of time, a node with the highest energy as the clusterhead, which is also called a redirector. power consumption is saved since the residual power in the nodes is maximized.

The above schemes do save some energy. Yet some energy will also be wasted when the clusterheads are not located at the centers of the clusters. Each clusterhead will then need to take more power to cover the range of the whole cluster.

C. *CDMA and TDMA schemes*

CDMA and TDMA [9-10] technologies are also applied to cluster protocol to prolong the lifetime of the network.

A. Hasan et al [9] adapt CDMA to save the energy of the ad hoc network. Power aware clustered TDMA (PACT) proposed by G. Pei and C. Chien [10] also prolongs the lifespan of the network by adapting the duty cycle to the user traffic. In other words, the radio is powered off if the network is inactive. Passive clustering is also applied to take advantage of the redundant dense topology and prolong the lifetime of the entire network. At a given time, only a subset of network nodes participate in the communication. The role of clusterheads and gateways is rotated according to their energy levels. The clustering requires no explicit control messages and therefore incurs negligible energy overhead.

D. *Other cluster schemes*

In the “passive clustering” schemes by Gerla et al [11], no periodic, background protocol dependent control packets or signals are required; thus, the overheads are reduced. Energy can be saved by reducing the data re-transmssion. Chang and Hsu [12] uses a dynamic routing group to communicate with other routing groups via the boundary mobile hosts as forwarding nodes. Passive clustering scheme is designed by T. J. Kwon and M. Gerla in [13] to reduce the redundant rebroadcast effect in flooding.

Distributed Dynamic Routing (DDR) [14] is an alternative simple loop-free bandwidth-efficient distributed routing algorithm for mobile ad hoc networks, based on forest construction of mobile nodes. It combines two main notions: zone and forest. Zones are used in order to reduce the delay due to routing process and to reach high scalability. Forest gives an appropriate structure to the mobile ad hoc network that allows a better radio resource utilization. The non-overlapped zones are dynamically constructed in relation with the forest.

Mieso K. Denko [15] adapts mobile agents for clustering in his research. Energy-aware topology management approach based on dynamic node priorities is proposed by in [16]. K-tree core [17] is a distance minizing structure. In this design, Sauabh et al propose a two-tier hierarchical routing scheme based on this core, while at the same time restricting flooding of control packets and utilizing the low overhead of on-demand algorithms.

III. DRAWBACKS OF EXISTING CLUSTER PROTOCOLS

A cluster algorithm consists of two phases: the set up and the maintenance. Any node can become a clusterhead if it has the necessary functionality, such as processing and transmission power.

Overlap is a problem of cluster scheme in ad hoc networks. It involves two types, as illustrated in Figure 2 and Figure 3.

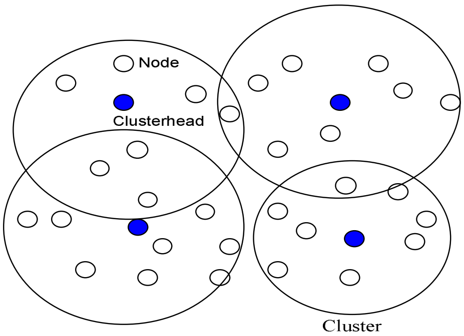

Fig. 2. Overlap in Cluster scheme (1).

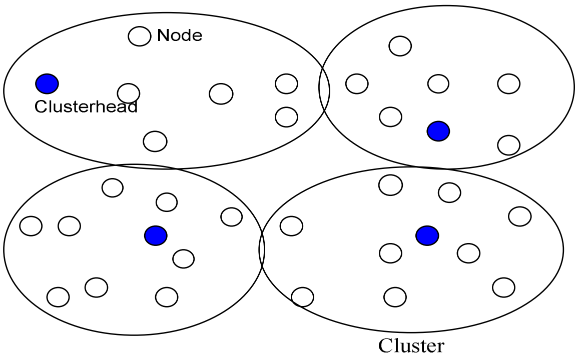

Fig. 3. Overlap in Cluster scheme (2).

As shown in Figure 2, some nodes are included into more than one cluster; energy is wasted in re-transmitting data to more than one clusterheds the overlap nodes belong.

The clusters organized by the ID number of nodes are shown in Figure 3. This design seems to show no overlap between any clusters. Yet the cluster is in fact not a cycle. The clusterhead will need to have a longer transmission range to cover the whole cluster and this power range will therefore cover some nodes in other clusters, as shown in Figure 4. Energy is again wasted.

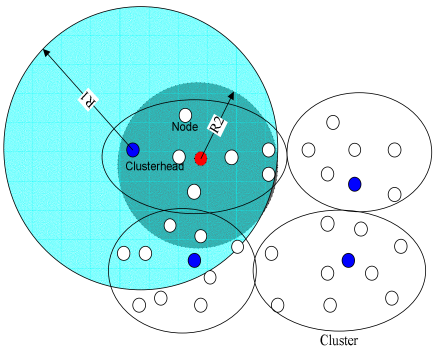

Fig. 4. Power Wasted in cluster scheme.

Another issue is that the power consumption of clusterheads is more than normal nodes. If the clusterheads run out of energy earlier, the clusters will be broken.

We therefore consider the following three issues in our TDC deign:

1) In each cluster, the clusterhead should be set at the center of the cluster at any time.
2) Because the power consumption of the clusterhead is higher than normal nodes, we should rotate the ordinary nodes as clusterheads while still keeping the advantage of the first issue.
3) There is only one route available from the source to the destination. Energy can be saved by reducing data re-transmission.

Thus the energy efficiency of the whole network is improved to extend the lifetime of the network.

IV. Energy-Efficienct TDMA Dynamic Cluster Protocol

The TDMA Dynamic Cluster protocol combines the following schemes: No-overlap cluster schemes, TDMA Dynamic Cluster scheme, TDC Scheduling scheme, TDC Directional Route and Free Collision scheme.

A. *No overlap cluster scheme*

This scheme aims to solve the problem of overlap.

Assume the nodes are evenly distributed in the network, with distance *d* of separation between them. The network selects the nodes with two nodes separating them to be clusterheads. Therefore, there are two nodes between neighboring clusterheads. In each cluster, the power range of the clusterhead is limited to $\sqrt{2}d$, which covers the whole cluster (here we neglect the size of the node.). The distance of two neighbouring clusterheads is *3d* and there are 9 nodes in each cluster, as shown in Figure 5.

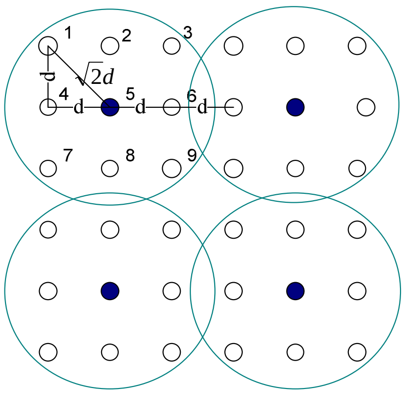

Fig. 5. No overlap cluster scheme.

From this scheme, we not only place the clusterheads at the centers of clusters, but also solve the issue of overlap.

B. *TDMA Dynamic Cluster Scheme*

To extend the life of the network, we should let all the nodes in each cluster to take turn to be the clusterhead to average the power consumption. Otherwise, the clusterhead will be out of power more quickly than the ordinary nodes, resulting in the disappearance of the cluster. We use TDMA technology in our design.

Figure 6 shows the first cycle of TDC design described above.

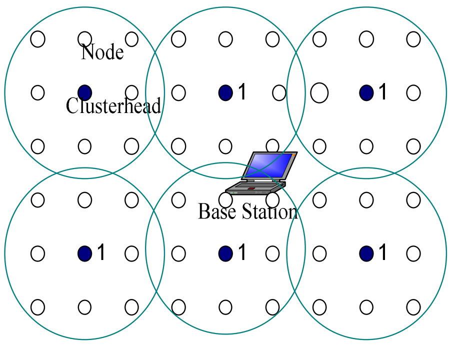

Fig. 6. First Period of TDMA Dynamic Cluster.

Figure 7 shows the beginning of the second cycle at which a different node in the cluster will be set as the new clusterhead for the new period. In this figure, the number 1 (blue) nodes and number 2 (red) nodes are the 1st the 2nd period clusterheads, respectively. The range is kept as the same value as the first period.

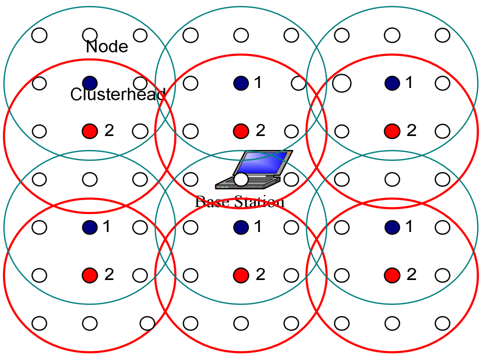

Fig. 7. Second Period of TDMA Dynamic Cluster.

New clusterheads will be selected at the beginning of the 3rd period, as shown in Figure 8. The number 3 (green) nodes represent the clusterheads of 3rd period.

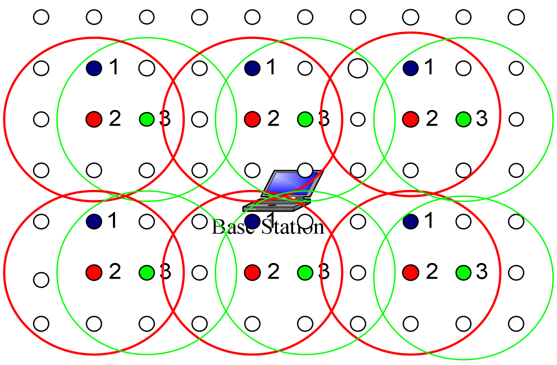

Fig. 8. Third period of TDMA Dynamic Cluster.

Succeeding, new clusterheads will continue to be selected at the beginning of each period. Figure 9 shows one way of setting the nodes in a cycle as the clusterhead in the cluster.

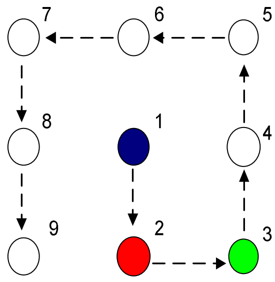

Fig. 9. Cycles of the whole cluster.

C. *TDC Scheduling Algorithm*

There are 9 nodes in each cluster; a node can only serve as clusterhead during the designated time slot.

Our scheduling algorithm is described in Figure 10. Each frame contains the ID of the node (A), information of the residual energy (B), and the timeslots (1-9).

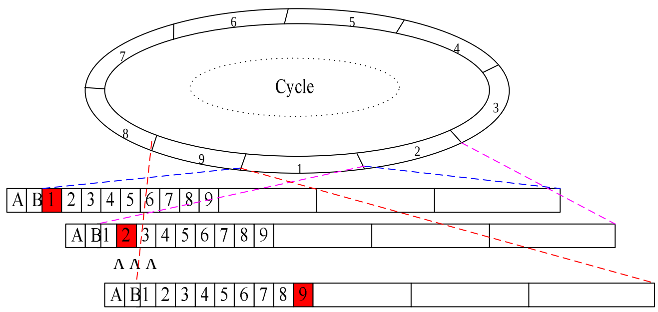

Fig. 10. One Cycle of TDMA Cluster.

D. *TDC Directional Route and Free Collision Schemes*

These schemes aim at saving energy by avoiding multiple transmissions of the data.

We set the ID number of the nodes according to their distance to the base station, as shown in Figure 11. The ID number of a node increases with its distance from the base station. A node farther further away from the base station will have a higher ID number than a nearer node.

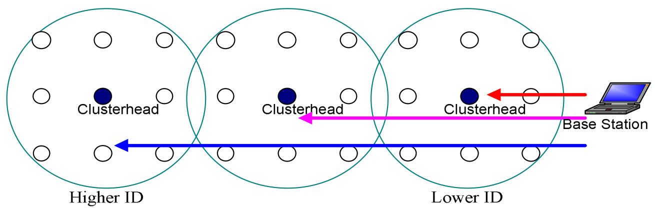

Fig. 11. ID Scheme in TDC.

The clusterhead has two transmission ranges: one range is $\sqrt{2}d$, the other is $3d$. The first range is to collect the data from normal nodes within its cluster. The second range is to send or transfer to the next hop (clusterhead) data it has collected from normal nodes or received from other clusterheads.

Collision will happen owing to multiple routes. From Figure 12, we find that, clusterhead 1 has two routes to transfer the data: it can send data towards the base station either to clusterhead 2 or to clusterhead 3. If both happen, some energy will be wasted by multiple transmissions of data.

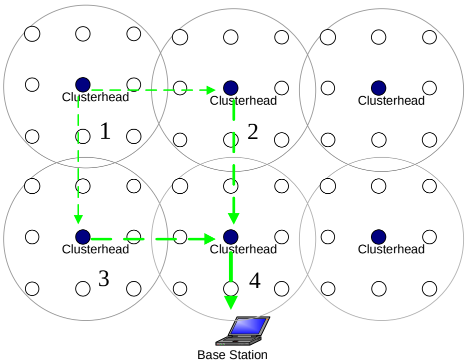

Fig. 12. Route Collision.

In order to avoid multiple routes in this scheme, only the clusterheads with lower ID can receive the data. In our free collision scheme, the clusterhead with higher residual energy has the privilege to receive the data from cluster 1. Thus there is only one route for clusterhead 1 and no data are multiply transmitted. Energy is saved.

V. Future Improvement of TDMA Dynamic Cluster

In our design, we assume the distribution of nodes in the network is uniform. The problem arises when different clusterheads have different power consumptions according to their distance to the base station.

The clusterheads form the backbone of the whole network. They have three important functions: generating data, collecting data from normal nodes, and transferring data to the next hop, as shown in Figure 13.

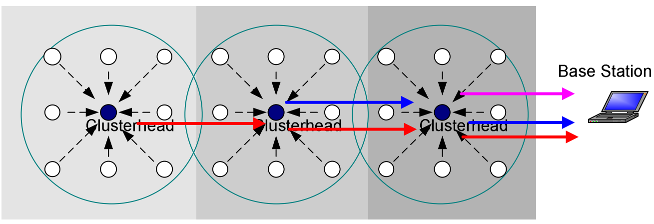

Fig. 13. Function of Clusterheads.

From the figure we see that the nearer the clusterhead is to the base station, the more data it should send or transfer. Since power consumption is related to the amount of data it sends, more data means more energy consumption. Thus the power consumption of clusterheads varies according to their distance to the base station. If the clusterheads in some areas are out of power earlier than others, the whole network will still lose its connectivity because of the RF limitation of clusterheads.

We should consider this question to improve our design.

VI. Conclusion and Future Work

We have proposed a new cluster protocol of ad hoc wireless networks, named TMDA Dynamic Cluster (TDC). This protocol aims to save energy through a combination of cluster and TDMA technologies.

This design improves the existing cluster protocol. In this scheme, nodes are distributed uniformly in the network. At any time, each clusterhead is set at the center of its cluster and there are no overlaps of clusters. Within a cluster, each node becomes the clusterhead by taking turns with a TDMA scheduling scheme to average the power consumption. Each clusterhead has a unique route to transfer data to the base station, thus avoiding re-transmitted of data through multiple routes. Energy is saved.

We also analyze some existing problems in our design. Future work will try to solve these issues, complete simulation and implement this scheme to other classic protocols.

References

[1] C. F. Chiasserint, I. Chlamtac, P. Monti, A. Nucci, "An energy-efficient method for nodes assignment in cluster-based Ad Hoc networks," Wireless Networks, Hingham, USA, 2004, pp 223-231.

[2] K. Liu and J. Li, "Mobile Cluster Protocol in Wireless Ad Hoc Networks," Available at: www.ifip.or.at/con2000/icct2000/icct471.pdf.

[3] L. Ramachandran, M. Kapoor, A. Sarkar, A. Aggarwal, "Clusting Algorithms for Wireless Ad Hoc Networks," Proceedings of the 4th international workshop on Discrete algorithms and methods for mobile computing and communications, Boston, Massachusetts, United States , 2000 , pp. 54 – 63.

[4] C.F. Chiasserini, I.Chlamtac, P.Monti and A. Nucci, "Energy Efficient Design of Wireless Ad Hoc Networks," Processings of European Wireless, Feb. 2002.

[5] C. K. Toh, "Maximum Battery Life Routing to Support Ubiquitous Mobile Computing in Wireless Ad Hoc Networks," IEEE Communications Magazine, June 2001, pp 138-147.

[6] S. D. Muruganathan, D. C.F. Ma, R. I. Bhasin, A. O. Fapojuwo, "A centralized energy-efficient routing protocol for wireless sensor networks," IEEE Radio Communications, March 2005, pp S8-S13.

[7] W. R. Heinzelman, A. Chandrakasan and H. bALAKRISHNAN, "Energy-Efficient Communication Protocol for Wireless Misrosensor Networks," Processing 33rd Hawaii International Conference system Science, Jan. 2000.

[8] J. S. Liu, C. H. Richard Lin, "Energy-Efficiency clustering protocol in wireless sensor networks," Elsevier, Ad Hoc Networks, May 2005, Volume 3, pp371-388

[9] A. Hasan, K. Yang, J. G. Andrews, "Clustered CDMA Ad Hoc Network without Closed-Loop Power Control," Proc. IEEE MILCOM, pp. 1030 - 1035, Oct 2003.

[10] G. Pei, C. Chien, "Low Power TDMA in Large Wireless Sensor Networks," Proc. IEEE MILCOM, pp. 347 - 351, October 2001.

[11] M. Gerla, J. et al, "On-demand routing in large ad hoc wireless networks with passibe clustering," Processing of the IEEE International Conference on Wireless Communications and Networking, Vol. 1, pp. 100-105, 2000.

[12] Y. L. Chang, C. C. Hsu, "Routing in wireless/mobile ad-hoc networks via dynamic group construction," Mobile Networks and Applications, Hingham, USA, 2000, pp 27-37.

[13] T. J. Kwon, M. Gerla, "Efficient flooding with Passive Clustering (PC) in ad hoc networks," ACM SIGCOMM Computer Communication Review, New York, USA, 2002, pp 44-56.
[14] N. Nikaein, H. Labiod, Christian Bonnet, "DDR: distributed dynamic routing algorithm for mobile ad hoc networks," International Symposium on Mobile Ad Hoc Networking & Computing, Piscataway, NJ, USA, 2000, pp 19-27.
[15] M. K. Denko, "The use of mobile agents for clustering in mobile ad hoc networks," ACM International Conference Proceeding Series, Republic of South Africa, 2003, pp 241-247.
[16] L. Bao, J.J. Garcia-Lun-Aceves, "Topology Management in Ad Hoc Networks," Proceedings of the 4th ACM international symposium on Mobile ad hoc networking & computing, New York, USA, 2003, pp 129-140.
[17] S. Srivastava, R.K.Ghosh, "Cluster based routing using a k-tree core backbone for mobile ad hoc networks," Proceedings of the 6th international workshop on Discrete algorithms and methods for mobile computing and communications, New York, USA, 2002, pp14-23.

Dali Wei received his BSc. and MSc. at University of Electronic Science and Technology of China in 2000 and 2003, respectively and is currently a PhD candidate in the Department of Electrical Engineering, University of Cape Town, R.S.A.

H. Anthony Chan (M'94–SM'95) received his PhD in physics at University of Maryland, College Park in 1982 and then continued post-doctorate research there in basic science.

After joining the former AT&T Bell Labs in 1986, his work moved to industry-oriented research in areas of interconnection, electronic packaging, reliability, and assembly in manufacturing, and then moved again to network management, network architecture and standards for both wireless and wire line networks. He designed the Wireless section of the year 2000 state-of-the-art Network Operation Center in AT&T. He was the AT&T delegate in several standards work groups under 3rd generation partnership program (3GPP). During 2001-2003, he was visiting Endowed Pinson Chair Professor in Networking at San Jose State University. In 2004, he joined University of Cape Town as professor in the Department of Electrical Engineering.

Prof. Chan is Administrative Vice President of the IEEE CPMT Society and has chaired or served numerous technical committees and conferences. He is a distinguished speaker of the IEEE CPMT Society and has been in the speaker list of the IEEE Reliability Society since 1997.