Topology-Transparent Scheduling in Mobile Ad Hoc Networks with Unidirectional Links

Yiming Liu[1(✉)], Zhi Fu[1], and Mao Yang[2]

[1] China Academy of Information and Electronics Technology, Beijing 100041, People's Republic of China
liuyiming09@tsinghua.org.cn

[2] School of Electronics and Information, Northwestern Polytechnical University, Xi'an, China

Abstract. In this paper, a novel efficient transmission scheduling algorithm for multihop mobile ad hoc networks (MANETs) with unidirectional links (ULs) is introduced. We propose an algorithm employing topology-transparent scheduling and erasure coding to support throughput guarantee over ULs in multihop MANATs. Our proposed algorithm can work over both unidirectional and bidirectional links, for both unicast and broadcast scenarios. We analytically study the performance of the proposed algorithm and achieve the maximum guaranteed throughput, for both unicast and broadcast scenarios. Simulations show that the proposed algorithm performs better than other topology-transparent algorithms over unidirectional links.

Keywords: Topology-transparent scheduling · Erasure coding
Unidirectional links

1 Introduction

Unidirectional links exist commonly in ad hoc networks for many reasons, such as heterogenous transmission powers [14], interference, and stealth considerations [12]. Almost all medium access control (MAC) protocols do not function well over unidirectional links, due to the nonexistence of feedback links and more serious hidden terminal problem [14,16].

Recently, many routing protocols [7,12,16] have been proposed to employ ULs to improve the throughput of ad hoc networks. However, there are very few efforts on channel access protocols capable of efficient and reliable data transmissions over unidirectional links.

Transmission scheduling protocols can be divided into two categories, namely, contention-based protocols and schedule-based protocols. Contention-based approaches, such as Carrier Sense Multiple Access (CSMA), are not suitable over unidirectional links, due to their dependence on feedback from the

B. Li et al. (Eds.): ChinaCom 2017, LNICST 237, pp. 112–121, 2018.
https://doi.org/10.1007/978-3-319-78139-6_12

receiver. Without the feedback from the receiver, the sender cannot decide whether packets have collided or not. In addition, Xu and Saadawi [17] have shown that contention-based approaches suffer from serious instability and unfairness issues in multi-hop MANETs. Schedule-based protocols, applying colouring theory to allocate time slots to each node such that the transmissions from these nodes are collision-free, are not suited to ad hoc networks with unidirectional links. This is because such approaches rely on handshakes among the neighbours, and only function correctly under the assumption that links are bidirectional.

Some contention-based protocols were proposed to improve the performance of conventional CSMA, by providing end-to-end feedback in the network or transport layer, but they are very complex in ad hoc networks and introduce unacceptable overhead and delay [5,13–15]. Bao and Garcia-Luna-Aceves [1] proposed PANAMA, an algorithm which attempts to provide collision-free dynamic channel access scheduling algorithm. In PANAMA, each user generates its priority randomly and wins the contention in each time slot, if its priority is the highest among all contenders. However, it is impractical due to the following facts. First, it is assumed that each user already knows the set of its contenders, but it is difficult, if not impossible, to collect such information in mobile ad hoc networks due to the dynamic topologies and the existence of unidirectional links. Moreover, each user is assumed to know automatically the priorities of its contenders in each time slot. It cannot be implemented at all in practice, since gathering such information takes much longer than a time slot (8 ms in [1]). Even if one assumes that the aforementioned information can be collected at each time slot without any overhead, PANAMA fails to support throughput guarantee and cannot function well. When the link from the hidden terminal to the receiver is unidirectional, the hidden terminal cannot know the existence and priority value of the sender and may consider itself as having the highest priority, resulting in collisions. In addition, packets in a particular node may suffer extremely long delay when the network load is heavy, because the node may lose the contentions repeatedly.

Conventional topology-transparent scheduling algorithms [2,3,6,8–10] can handle unidirectional links in mobile ad hoc networks. However, the sender does not know whether its packet can be successfully received by its neighbour(s) in a particular time slot, due to the lack of acknowledgements over unidirectional links. This implies that these algorithms are very inefficient, since each sender may have to transmit one packet repeatedly in one frame time.

In this work, we employ topology-transparent scheduling and erasure coding together to combat the nonexistence of feedback channels, implementing an efficient and reliable channel access algorithm in ad hoc networks with unidirectional links. The important features of our proposed algorithm are listed as follows:

(1) Our algorithm is distributed, does not rely on detailed network connectivity information, and is thus adaptive to the network topology changes.

(2) Our algorithm does not rely on the feedback from the receiver, and thus can handle unidirectional links in ad hoc networks.
(3) Our algorithm can be applied over bidirectional links as well as unidirectional links.
(4) Our algorithm achieves the same guaranteed throughput for both unicast and broadcast traffics.

We study the performance of our proposed algorithm analytically, and achieve the maximum guaranteed throughput of both unicast and broadcast traffics. The analytical and simulation results show that our proposed algorithm outperforms other existing algorithms over unidirectional links and achieves the same guaranteed throughput as those of other existing topology-transparent scheduling algorithms over bidirectional links.

2 System Model

2.1 Network Model

A mobile ad hoc network with unidirectional links can be represented by a directed graph $G(V, E)$, where V is the set of network nodes ($|V| = N$) and E is the set of directional links between nodes. If $(v, u) \in E$, u is an interfering neighbour of v. Note that $(v, u) \in E$ does not necessarily mean $(u, v) \in E$ in networks with unidirectional links. We define the degree of a node v, $D(v)$, as the number of interfering neighbours of v. The maximum degree $D_{\max}$ is defined as $\max\limits_{v \in V} d(v)$, and is assumed to be much smaller than N. In practice, the value of $D_{\max}$ can be estimated according to the network density and heterogenous interference ranges in the networks. We introduce a method to estimate the value of $D_{\max}$ in the following section. Due to space limitations, the effect of inaccurate estimation of $D_{\max}$ on the network throughput is left for future work. Hereafter, $D_{\max}$ is assumed to remain constant, despite the fact that the network topology may change frequently [4].

Time is divided into frames, and each frame consists of equal-sized synchronized time slots. The synchronization can be achieved by using GPS or other commonly used approaches. For the transmissions over unidirectional links, acknowledgements are not available.

With the assumption that a reception failure is only resulted from transmission collisions, we can see that the transmission from Node u to Node v will be successful if and only if (1) Node v is not in the transmission mode and (2) other interfering neighbours of v are not in the transmission mode either.

2.2 Erasure Coding

According to the Singleton bound [11], we can use an $[n, k, d]$ maximum distance separable (MDS) code to protect k elements with $n-k$ redundant elements, if the minimum distance of the code, d, is set as $d = n - k + 1$. We apply Cauchy MDS erasure code here [11]. Let $G_{k\times n} = (I_{k\times k}|C_{k\times(n-k)})$ be the generator matrix of used $[n,k,d]$ Cauchy code, where $I_{k\times k}$ is an identity matrix and $C_{k\times(n-k)}$ is a Cauchy matrix, respectively [9]. A vector $\mathbf{x_k}$ consisting of k elements can be encoded to a vector $\mathbf{y_n}$ consisting of n elements as follows:

$$\mathbf{y_n} = \mathbf{x_k}\mathbf{G_{k\times n}}. \tag{1}$$

The first k elements of the encoded vector $\mathbf{y_n}$ are just the k original elements of $\mathbf{x_k}$, and the other $n-k$ elements of $\mathbf{y_n}$ are encoded redundant elements.

For the decoder, given any k out of n elements of the vector $\mathbf{y_n}$ received (denoted as $\mathbf{y_k}$), the original vector can be decoded successfully. Keeping the columns and the rows of the generator matrix $G_{k\times n}$ according to these k elements and deleting the other columns and rows, we thus get a $k\times k$ matrix $G'_{k\times k}$. Since the Cauchy code employed is an MDS code, $G'_{k\times k}$ is always invertible [11]. The detailed decoding is as follows:

$$\mathbf{x_k} = \mathbf{y_k}(\mathbf{G'_{k\times k}})^{-\mathbf{1}}. \tag{2}$$

Note that even if less than k encoded elements are received, the original vector can be decoded partially. If the i-th element of the encoded vector $\mathbf{y_n}$, where $i = 1, 2, \cdots, k$, is received successfully, the corresponding i-th element in the original vector $\mathbf{x_k}$ can be decoded correctly, since it is equal to the i-th element of the encoded vector $\mathbf{y_n}$.

3 Proposed Algorithm

3.1 Frame Structure

In this paper, we consider a TDMA MANAT with unidirectional links, $G(V,E)$. We divide a frame into q subframes, and each subframe consists of p time slots. Assign each node v a unique polynomial of degree k over Galois Field $GF(p)$ (p is a prime or prime power), $f_v(x) = \sum_{i=0}^{k} a_i x^i (\mathrm{mod} p)$, where $v \in V$, which is called as time slot assignment function (TSAF) [6]. Therefore, Node v transmits in the time slot $f_v(i)$ in Subframe i, where $i \in \{0,1,2,\ldots,q-1\}$ [6]. Each node, thus, transmits q times in one frame time. The frame structure is shown in Fig. 1.

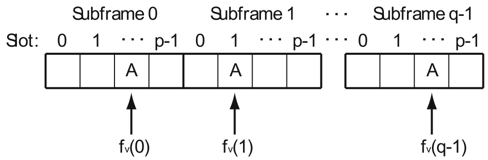

Fig. 1. The frame structure.

In order to assign a unique polynomial to each user, $p^{k+1} \geq N$ has to be satisfied. There are at most k conflicts between any two nodes during one frame if $q \leq p$ [6]. Each node has at most $D_{\max}$ interfering neighbours. Therefore, the number of possible collisions of one node in one frame time is less than or equal to $kD_{\max}$. We set $q \geq kD_{\max} + 1$ to ensure that every node can have at least one collision-free time slot to transmit data to all neighbours successfully during one frame. This guarantee only depends on N and $D_{\max}$, despite the fact that network topology may change frequently. This is why we call it topology-transparent scheduling.

Each node encodes M queued packets in its buffer using a $[q, M, q - M + 1]$ Cauchy code and transmits the i-th encoded packet in Subframe $i - 1$, where $i = 1, 2, \cdots, q$. We assume that there are always M data packets queued in the buffer at each node in every frame, for encoding and transmission. In order to ensure that all M packets are received correctly, we set $M = q - kD_{\max}$.

3.2 Estimation of the $D_{\max}$

$D_{\max}$ is the most important design parameter of the proposed algorithm. The reliability and efficiency of the proposed algorithm rely on the accuracy of the estimation of $D_{\max}$. However, none of the previous work on topology-transparent scheduling elaborates on how to estimate the value of $D_{\max}$ accurately, making such scheduling difficult to be implemented in practice. In this section, a method to estimate the value of $D_{\max}$, according to the network density and heterogeneous interference ranges in the networks, is introduced.

Suppose that an MANET with unidirectional links consists of n classes of nodes, C_i, where $i = 1, 2, \cdots, n$. We assume that the nodes in each class are distributed as a two-dimensional Poisson point process with the density λ_i. The interference range of nodes in C_i is R_I^i. Let d_i be the number of interfering neighbours of a given node of Class C_i. Thus, the probability that there are y nodes interfering a given node is given as follows:

$$\Pr(\sum_{i=1}^{n} d_i = y) = \frac{[\pi \sum_{i=1}^{n} \lambda_i (R_I^i)^2]^y}{y!} e^{-\pi \sum_{i=1}^{n} (R_I^i)^2}. \quad (3)$$

Given λ_i and R_I^i, we choose $D_{\max}$ as the smallest integer satisfying $Pr(\sum_{i=1}^{n} d_i > D_{\max}) < \alpha$, where α is a given threshold. For example, when $n = 2$, $\lambda_1 = \lambda_2 = 2 \times 10^{-5}\,\mathrm{m}^{-2}$, $R_I^1 = 100\,\mathrm{m}$, $R_I^2 = 200\,\mathrm{m}$, and $\alpha = 0.01$, $D_{\max}$ is estimated as $D_{\max} = 9$.

In practical, statistics and empirical data can be applied for the estimation of $D_{\max}$. Additionally, $D_{\max}$ is always estimated pessimistically based on network parameters, in order to ensure that the actual number of interfering neighbours is not larger than the estimation.

3.3 Analysis of Proposed Algorithm

In the following, we analyze the guaranteed throughput of the proposed algorithm in the unicast scenario first, and then in the broadcast scenario. Note that $M = q - kD_{\max}$ collision-free slots are guaranteed within one frame time. Thus, all M packets can be received and decoded correctly within one frame time. We obtain the guaranteed throughput per node of the proposed algorithm as follows:

$$G = \frac{q - kD_{\max}}{pq}. \tag{4}$$

In order to achieve the optimal guaranteed throughput, we have Theorem 1 as follows.

Theorem 1: For given N and $D_{\max}$,

(1) Fixing p, the maximum guaranteed throughput is achieved when $q = p$.
(2) When $N^{\frac{1}{k+1}} \geq 2kD_{\max}$, the maximum guaranteed throughput is achieved when $p = p_1$, where p_1 is the smallest prime or prime power not less than $N^{\frac{1}{k+1}}$; when $N^{\frac{1}{k+1}} < 2kD_{\max}$, the maximum guaranteed throughput is achieved when $p = p_2$, where $p_2 = \arg \max_{p \in \{p_3, p_4\}} G(p)$, p_3 is the largest prime or prime power less than $2kD_{\max}$, and p_4 is the smallest prime or prime power not less than $2kD_{\max}$.
(3) The optimal value of k maximizing the guaranteed throughput (G) is less than or equal to $\lceil k_0 \rceil$, where k_0 is the root of $2kD_{\max} = N^{\frac{1}{k+1}}$.

Proof

(1) Given p, we have: Noting that $q \leq p$, we conclude that the maximum guaranteed throughput is achieved when $q = p$.
(2) In order to achieve the maximum guaranteed throughput, we have to solve the following equation:

$$\frac{\partial G}{\partial p} = \frac{\partial \frac{p - kD_{\max}}{p^2}}{\partial p} = 0. \tag{5}$$

Thus, $p = 2kD_{\max}$. Note that $p \geq max(N^{\frac{1}{k+1}}, kD_{\max} + 1)$. If $N^{\frac{1}{k+1}} \geq 2kD_{\max}$, G decreases with increasing p, and thus the maximum value of G is obtained when $p = N^{\frac{1}{k+1}}$. If $N^{\frac{1}{k+1}} < 2kD_{\max}$, the maximum value of G is obtained when $p = 2kD_{\max}$. Recalling that p is a prime or prime power, we prove 2) of Theorem 1.

(3) $2kD_{\max}$ increases and $N^{\frac{1}{k+1}}$ decreases with increasing k. If $k \geq \lceil k_0 \rceil$, $2kD_{\max} > N^{\frac{1}{k+1}}$. Thus, the maximum value of G is achieved when $p = 2kD_{\max}$, i.e.,

$$G_{max} = \frac{kD_{\max}}{4k^2 D_{\max}^2} = \frac{1}{4kD_{\max}}, \tag{6}$$

which decreases with increasing k. For all $k > \lceil k_0 \rceil$, $G(k) < G(\lceil k_0 \rceil)$. This means that the optimal value of k maximizing the guaranteed throughput (G) is less than or equal to $\lceil k_0 \rceil$.

Thus, we proposed a topology-transparent scheduling algorithm with erasure coding over ULs, which achieves the maximum guaranteed throughput as follows.

(1) For given N and $D_{\max}$, apply Theorem 1 to obtain the optimal k, p and q, where $q = p$.
(2) Assign each node a unique degree-k TSAF randomly.
(3) Calculate the TSLV of each node, according to the aforementioned method.
(4) Each node encodes $M = q - kD_{\max}$ packets to q packets and transmits the i-th encoded packet at the selected slot in Subframe $i-1$, where $i = 1, 2, \cdots, q$.

3.4 Discussion

Considering broadcast traffic, at least $M = q - kD_{\max}$ collision-free time slots are guaranteed within one frame time for the transmission from a node to each of its neighbours. Therefore, M, out of q, packets can be received successfully and decoded by each of its neighbours within one frame time. Theorem 1 also holds for broadcast traffic. Thus, our algorithm is suitable for both unicast and broadcast traffics and achieves the same guaranteed throughput.

Our algorithm does not rely on any feedback channels. This implies that our algorithm works correctly over both unidirectional and bidirectional links. The proportion of unidirectional links does not effect the performance of the proposed algorithm.

To conclude, our algorithm is well suited over both unidirectional and bidirectional links, in both unicast and broadcast scenarios.

4 Performance Evaluation

In this section, we compare by simulations the proposed algorithm with the topology-transparent algorithm proposed in [2] (referred to as MGD) and the conventional TDMA fixed assignment scheme, both of which support guaranteed throughput over unidirectional links. We study the impact of different settings of N and $D_{\max}$ on the maximum guaranteed throughput of our algorithm. Unlike the proposed algorithm and aforementioned algorithms, none of the contention-based protocols [5,13,14] and PANAMA [1] can support throughput and delay guarantees over the unidirectional links, and are therefore not included as comparisons.

4.1 Simulation Setup

We apply the Gauss-Markov mobility model, which is more realistic than the widely used Random Waypoint model. All nodes are distributed in a region of $1000\,\text{m} \times 1000\,\text{m}$, uniformly and randomly.

In order to model the existence of unidirectional links, half of N nodes are with higher transmission power, and the other half with lower transmission power. Let R_T^h and R_T^l be the transmission ranges, and R_I^h and R_I^l be the interference ranges of higher power nodes and lower power nodes, respectively. We set $r = \frac{R_T^h}{R_T^l} = \frac{R_I^h}{R_I^l} = 2$ in the simulation. In fact, our algorithm does not rely on any feedback and operation over unidirectional links such that the proportion of unidirectional links has no effect on the performance of the proposed algorithm. Thus, there are no differences in the operation and performance between the nodes with higher transmission power and lower transmission power, and the simulation results correspond to the average values of all N nodes.

We apply the optimal parameters (k and $p = q$) achieving the maximum guaranteed throughput, which are calculated according to Theorem 1. Each simulation lasts for 300 frames.

4.2 Simulation Results

1. Effect of N on Guaranteed Throughput

Given that $D_{\max} = 8$, and N is set with eight different values from 100 to 800, we study the performance of the proposed algorithm, in terms of maximum guaranteed throughput. Figure 2 shows that the proposed algorithm outperforms other algorithms, including MGD and the conventional TDMA. For the case of $N = 400$ and $D_{\max} = 8$, the guaranteed throughput of the proposed algorithm is almost six times better than that of MGD. The main reason of this superior performance is that we employ erasure coding and topology-transparent scheduling together to ensure that multiple packets rather than only one packet, as in MGD, are received and decoded successfully within a frame time, independently of the existence of the feedback channel over unidirectional links. Moreover, we can see that the performance of the proposed algorithm deteriorates with increasing N slowly, which implies that the performance of our algorithm is not very sensitive to the number of nodes in the network.

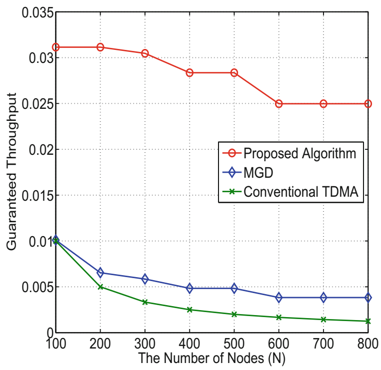

Fig. 2. The effect of N on the maximum guaranteed throughput.

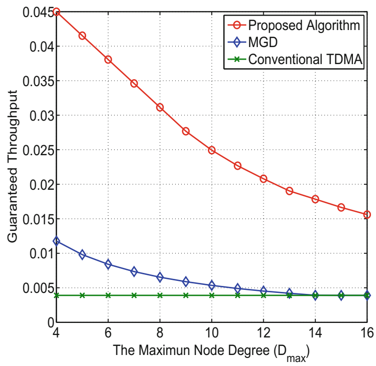

Fig. 3. The effect of $D_{\max}$ on the maximum guaranteed throughput.

2. Effect of $D_{\max}$ on Guaranteed Throughput
Given that $N = 256$, we study the performance of the algorithm with $D_{\max}$ varying from six to 16. A larger $D_{\max}$ implies a denser network and more possible collisions. As observed in Fig. 3, the proposed algorithm performs better than MGD and the conventional TDMA. The guaranteed throughput of the proposed algorithm is four times and three times better than that of MGD, for the cases of $(N = 256, D_{\max} = 4)$ and $(N = 256, D_{\max} = 16)$, respectively. Compared with Fig. 2, we can observe that $D_{\max}$ has a much greater impact on the guaranteed throughput than N.

5 Conclusion

In this paper, we propose a way to employ topology-transparent scheduling and erasure coding together as an efficient and reliable transmission scheduling algorithm in mobile ad hoc networks with unidirectional links. Unlike other previous scheduling algorithm over unidirectional links, our algorithm does not rely on detailed network connectivity information and is adaptive to network topology changes. The proposed channel access algorithm does not rely on the existence of feedback channels, and can support guaranteed throughput for both unicast and broadcast traffics over both unidirectional and bidirectional links. We show that our algorithm performs best, compared with other algorithms supporting guaranteed throughput over unidirectional links.

Acknowledgement. This research is supported in part by the National Natural Science Foundation of China, under Grand No. 61501415.

References

1. Bao, L., Garcia-Luna-Aceves, J.J.: Channel access sheduling in ad hoc networks with unidirectional links. In: 5th ACM International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIALM 2001), Rome, pp. 9–18 (2001)
2. Cai, Z., Lu, M., Georghiades, C.: Topology-transparent time division multiple access broadcast scheduling in multihop packet radio networks. IEEE Trans. Veh. Technol. **52**(4), 970–984 (2003)
3. Chalamatac, I., Farago, A.: Making transmission schedules immune to topology changes in multi-hop packet radio networks. IEEE/ACM Trans. Netw. **2**(2), 23–29 (1994)
4. Chou, A.M., Li, V.O.K.: Fair spatial TDMA channel access protocols for multihop radio networks. In: IEEE INFOCOM 1991, Bal Harbour, pp. 1064–1073 (1991)
5. Fujii, T., Takahashi, M., Bandai, M., Udagawa, T., Sasase, I.: An efficient MAC protocol in wireless ad hoc networks with heterogeneous power nodes. In: IEEE WPMC 2002, Honolulu, vol. 2, pp. 776–780 (2002)
6. Ju, J.H., Li, V.O.K.: An optimal topology-transparent scheduling method in multhop packet radio networks. IEEE/ACM Trans. Netw. **6**(3), 298–306 (1998)

7. Lin, C., Liu, B., Yang, H., Kao, C., Tsai, M.: Virtual-coordinate-based delivery-guaranteed routing protocol in wireless sensor networks with unidirectional links. In: IEEE INFOCOM 2008, Phoenix, pp. 351–355 (2008)
8. Liu, Y., Li, V.O.K., Leung, K.C., Zhang, L.: Distributed multi-channel topology-transparent broadcast scheduling in ad hoc networks. In: IEEE Wireless Communications and Networking Conference (IEEE WCNC 2014), Istanbul (2014)
9. Liu, Y., Li, V.O.K., Leung, K.C., Zhang, L.: Topology-transparent scheduling in mobile ad hoc networks with multiple packet reception capability. IEEE Trans. Wireless Commun. **13**(11), 5940–5953 (2014)
10. Liu, Y., Weng, L., Li, V.O.K., Xu, S.: Topology-transparent scheduling in mobile multihop ad hoc networks with directional antennas. In: IEEE Wireless Communications and Networking Conference (IEEE WCNC 2016), Doha (2016)
11. MacWilliams, F.J., Sloane, N.J.A.: The Theory of Error-Correcting Codes. North Holland Publishing Co., Amsterdam (1977)
12. Marina, M., Das, S: Routing performance in the presence of unidirectional links in multihop wireless networks. In: ACM MOBIHOC 2002, Lausanne, pp. 12–23 (2002)
13. Poojary, N., Drishnamurthy, S.V., Dao, S: Medium access control in a network of ad hoc mobile nodes with heterogeneous power capabilities. In: IEEE ICC 2001, Helsinki, vol. 3, pp. 872–877 (2001)
14. Wang, G., Turgut, D., Boloni, L., Ji, Y., Marinescu, D.C.: A MAC layer protocol for wireless networks with asymmetric links. Ad Hoc Netw. **6**(3), 424–440 (2008)
15. Weng, L., Liu, Y., Liu, L., Wang, Z.: Wireless link quality estimation and prediction: a survey. J. Chin. Acad. Electron. Inf. Technol. **11**(3), 239–244 (2016)
16. Wu, J.: Extended dominating-set-based routing in ad hoc wireless networks with unidirectional links. IEEE Trans. Parallel Distrib. Syst. **13**(9), 866–881 (2002)
17. Xu, S., Saadawi, T.: Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks? IEEE Commun. Mag. **39**(6), 130–137 (2001)