INVITED PAPER

Multichannel Mobile Ad Hoc Links for Multimedia Communications

By using techniques that reduce interference from nearby wireless equipment, picture quality for streaming video can be improved in wireless computer networks.

By HAMID GHARAVI, *Fellow IEEE*

ABSTRACT | This paper is mainly concerned with multichannel transmission of real-time information such as video over multihop ad hoc links. We propose two multichannel routing protocols. The first is based on single-path routing and aims at suppressing the intrapath interference in a carrier sense multiple access/collision avoidance network. This is achieved by developing a link-partitioning scheme where nodes in the neighboring partitions operate at different nonoverlapping frequency bands. For this approach, we present a systematic channel assignment technique that has been specifically developed for the ad hoc on-demand distance vector routing protocol. It is shown that this partitioning scheme can considerably enhance the throughput performance of a multihop link. The second multichannel scheme is developed for transmission of real-time traffic over multiple-path routes. Bear in mind that multiple-path diversity routing has been shown to be very effective in dealing with network congestion in wireline Internet protocol networks. Unfortunately, in mobile ad hoc network environments, particularly for real-time traffic, this approach can suffer greatly from cochannel interference due to the simultaneous transmission of packets via multiple routes. In this respect, we have designed a dual-path routing protocol, which guarantees a different frequency band for each path, thus eliminating any interpath interference. We show that this protocol has an important property, which is reducing the probability of losing both routes at the same time. Based on this important property, we demonstrate that a combination of the routing protocol and dual-description video coding can greatly enhance the ad hoc network performance of video transmission for real-time traffic.

Manuscript received October 31, 2006; revised August 31, 2007.
The author is with the National Institute of Standards and Technology, Gaithersburg, MD 20899-8920 USA (e-mail: gharavi@nist.gov).

Digital Object Identifier: 10.1109/JPROC.2007.909877

KEYWORDS | Ad hoc video; interference cancellation; mobile ad hoc network (MANET); multichannel routing; multihop networks; multiple description coding (MDC); multiple-path routing

I. INTRODUCTION

Advances in wireless local-area network technology (typically based on IEEE 802.11) and growing interest in ad hoc networks for sensitive operations such as first responders and disaster recovery have created new demands for delivery of voice and video services over multihop ad hoc channels. However, due to the dynamic nature of these networks and a lack of network infrastructure (without a central administration), providing a reliable end-to-end real-time communication cannot be easily accomplished. These difficulties mainly arise from the fact that, under a varying network topology, maintaining link connectivity in the network over a relatively long period of time cannot be guaranteed. Even at times when the connectivity does exist, the transmission of real-time multimedia traffic may suffer from significant delay and large packet losses. Indeed, the problem is limited not only to the effect of harsh channel conditions which can be accelerated in a hop-by-hop transmission but also to carrier sense multiple access with collision avoidance (CSMA/CA) access protocol commonly used by the IEEE 802.11 family. This protocol controls access to the shared wireless medium [1], which makes it very sensitive to interference caused by other active nodes. Bear in mind that the principle of the CSMA/CA method is based on a "listen before talk" concept. This is aimed at reducing collisions by simultaneous transmission by multiple radios. In the shared wireless medium environments, the collision avoidance method operates in half-duplex in order to avoid interference by simultaneous transmission and reception by the same node. On the other hand, a half-duplex system does not prevent interference from other intermediate nodes that are involved in relaying packets to the next hop. In particular, in the case of continuous media communications, these interferences would create a bottleneck in the multihop link.

In our earlier investigations, we have shown that this situation can be effectively handled via the application layer by dynamically changing the source bandwidth in accordance with the number of hops from source to destination [2]. In fact, lowering the source bandwidth at the higher hop count reduces the probability that farther away nodes will interfere with each other. Although controlling the source bandwidth can improve link performance at the expense of fluctuating the received signal quality, the problem with interfering relay nodes remains a major challenge. There are a number of techniques such as power control and beamforming antenna that have considered in order to reduce the effect of interfering relay nodes [3], [4]. In this paper, however, we are mainly concerned with the multichannel approach to mitigate the effect of interferences from nearby relay nodes. In particular, we will focus on addressing the problem of the interferences not only in a single-path routing but also in a multiple-path routing diversity. In both cases, we assume that the CSMA/CA protocol is used at the media access control (MAC) layer. In addition, in the case of multiple-path diversity routing, we use multiple description coding (MDC) schemes to evaluate the performance of the protocol.

This paper is organized as follows: we first briefly review ad hoc routing schemes, particularly the ad hoc on-demand distance vector (AODV) [7] and dynamic source routing (DSR) [8] protocols, which have been used in our investigations. In Section III, we introduce an efficient multichannel routing protocol that deals with the effect of interfering relay nodes in single-path routing. The expansion of a multichannel assignment concept to multiple-path diversity routing is then presented in Section IV. We also present MPEG-4 based dual-description video coding schemes [48], which have been used to evaluate the performance of the multiple-path diversity routing protocol.

II. AD-HOC ROUTING PROTOCOL

Routing in mobile ad hoc network (MANET) has led to the development of many different routing protocols mainly through the efforts of the Internet Engineering Task Force [5]. The performance of these protocols generally depends on the network scenarios, node density, and network traffic. It can be broadly divided into two categories: flat routing and hierarchical routing.

In hierarchical routing protocols, nodes are classified in groups and each node has the information about the routers in its own group. For this reason, this class of routing protocols can reduce the size of routing table for large networks. In fact, further downsizing of the routing table can be accomplished by breaking down the network topology into a higher number of layers in the hierarchy (e.g., group, region, cluster, etc.). Nonetheless, increasing the number of hierarchical levels would result in higher communication overheads compared with flat routing [6].

In flat routing protocols, every node knows about other nodes in the network. They can be designed to function in a proactive or reactive (on-demand) manner. In the former case, the routing information is always maintained, and changes to the network will be updated with or without traffic. Updating a network is based on sending periodic control messages in order to maintain routes to every node in the network. Although this feature may seem to be well suited for real-time traffic, the rate at which these control messages are sent must keep up with the dynamics of the network. Thus, under a high degree of mobility, a fast update to allow a low-latency route access can lead to a significant increase in the network overhead.

In contrast, in reactive (on-demand) protocols, a route between nodes is initiated whenever there is a desire to establish a link. This is done via a routing discovery process, which is initiated whenever there is a need to transmit data packets to a destination. In a route discovery phase, the route request packets flood the network in search of a path. As soon as the path to the destination is identified, a route reply (RREP) message is sent in the reverse direction towards the source node. Another form of control message in on-demand routing is the route error (RERR) message. This message is generated as soon as a node along the path has detected a link failure. Under this condition, an RERR is sent in the upstream direction. Once the source node receives the RERR message, it will reinitiate the new route discovery process (it should be noted that a combination of the two routing strategies can form a hybrid routing where the local connectivity is proactively maintained, whereas for a faraway node the search is done reactively via a route discovery process).

Among many on-demand protocols, AODV [7] and DSR [8] protocols have been perceived as the most popular and well-developed routing protocols. There are a number of distinctions between the two protocols. For instance, in the DSR, every packet must carry the Internet protocol (IP) addresses of all the nodes along the multihop path (from the source to the destination), whereas in AODV, only the destination address is carried in each packet. Obviously, for a large network where there is a possibility of having a link with a high number of hops, DSR can lead to a significant increase in the packet overhead. At the same time, this protocol has the advantage of storing all the alternative routes from source to destination. This inherent multiple-path property makes this protocol very attractive for the multiple-path routing approach, which has been exploited in our multiband multiple-path routing protocol and will be discussed in Section III.

As far as the AODV protocol is concerned, it has the advantage of lower overhead. AODV is the table-driven routing protocol maintaining up-to-date routing information for every node. Updating the routing table is mainly to maintain neighbor connectivity and can be accomplished by frequent transmission of the beacon frame, which is also known as a "hello" message. Bear in mind that the use of hello messages is optional since maintaining the next hop connectivity in an active route can be achieved by other means such as the packet exchanges at the MAC layer (e.g., acknowledgment). Nonetheless, broadcasting "hello" messages, although at the expense of an increase in overhead, could provide a better connectivity to all the neighboring nodes.

In the AODV route discovery process, the source node first broadcasts an RREQ packet, which propagates throughout the ad hoc network until it reaches the destination node or any other intermediate node that has a route to the destination node. This node then sends an RREP message to the source node along the path that the RREQ has been propagated. It should be noted that nodes that have already received the RREQ, with the same originator IP address and RREQ ID (incremented for every RREQ the node initiates), would ignore the RREQ. Indeed, all the receiving nodes refresh their routing table entries with information such as the destination IP address, hop count, precursor, next hop, destination sequence number, etc. The main role of the destination sequence number is to ensure that all routes contain the most recent route information, preventing the formation of a routing loop [7]. In cases where there are more routes from the source to the destination, the source node may select the route with the minimum hop count (shortest path).

Comparisons between AODV and DSR protocols have been extensively evaluated in [9]–[12]. However, due to the popularity of this protocol, we have used this for our multiband routing scheme.

III. SINGLE-PATH MULTICHANNEL ROUTING AND PARTITIONING

Multichannel protocols have been extensively studied in the past [13]–[25]. Most of these protocols were concerned with MAC layer aspects of multichannel transmission systems, where a higher throughput can be accomplished by using multiple parallel communications on different channels. These schemes are generally based on designing a MAC protocol that allows mobile hosts to dynamically switch channels in accordance with the channel utilization. For example, in [20], the IEEE 802.11 MAC protocol was modified in such a way that one of the channels is dedicated to common access control (including RTS/CTS) and other channels to data communications. Li *et al.* [21] also use a similar approach, where they use a control channel (through RTS/CTS exchange) for channel negotiation and multiple data channels for data and acknowledgment (ACK) frames. A multichannel MAC protocol based on multiple transceivers [e.g., multiple network interface cards (NICs)] has also been investigated in [22]. In this approach, one channel is reserved as the control channel and each traffic channel is dedicated to one flow at any point of time. These protocols verify the fact that by utilizing multiple transceivers (e.g., NICs), it is possible to significantly improve the throughput performance, which has also been analytically investigated in [23]. Nonetheless, even with the help of these protocols, the problem with interferences from nodes that are more than one hop away (intrapath interference) still remains a major deteriorating factor in multihop transmission systems. Therefore, in this section, we present a multichannel allocation technique, which is based on a single transceiver (e.g., NIC).

Before describing the details of the protocol, let us first consider a wireless multihop link consisting of N nodes, where a stream of packets is transmitted from node 1 to node N. The signal-to-(interference plus noise) ratio (SINR) for the link $(i, i+1)$ can be shown as

$$\gamma_{i,i+1} = \frac{P_i/PL_{i,i+1}}{P_{\text{Noise}} + \sum_{k=1(k\neq i,i+1)}^{N} X_k P_k/PL_{k,i+1}} \quad 1 \le i \le N-1 \quad (1)$$

where P_{Noise} is the background noise at node $i+1$, P_i is the transmitting power at node i, $\boldsymbol{PL_{i,k}}$ is the propagation pathloss between node i and node k, and X_k is a binary variable, where

$$X_k = \begin{cases} 1, & \text{if node } k \text{ transmits} \\ 0, & \text{otherwise} \end{cases}. \quad (2)$$

Assuming that all nodes have the same receiving power P_0, we can show

$$P_0 = P_{i,i+1} = P_i/PL_{i,i+1}, \quad 1 \le i \le N-1. \quad (3)$$

Thus, the transmitting power P_i for node i is

$$P_i = P_0 PL_{i,i+1}, \quad 1 \le i \le N-1. \quad (4)$$

From (1)–(3), $\gamma_{i,i+1}$ can be shown

$$\gamma_{i,i+1} = \frac{P_0}{P_{\text{Noise}} + \sum_{k=1(k\neq i,i+1)}^{N} P_0 X_k (PL_{k,k+1}/PL_{k,i+1})} \quad 1 \le i \le N-1. \quad (5)$$

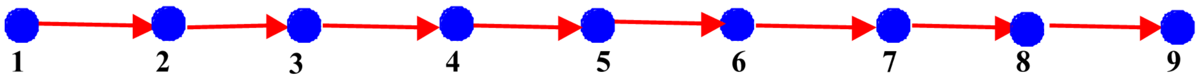

Fig. 1. ***Multihop link consisting of nine nodes.***

Furthermore, we can rewrite (5) as

$$\gamma_{i,i+1} = \frac{1}{P_{\text{Noise}}/P_0 + \sum\limits_{k=1(k\neq i,i+1)}^{N} X_k(PL_{k,k+1}/PL_{k,i+1})} \qquad 1 \leq i \leq N-1. \quad (6)$$

From (6), we can observe that $\gamma_{i,i+1}$ increases while increasing P_0. We can show the upper limit for $\gamma_{i,i+1}$ as

$$\gamma_{i,i+1} < \lim_{P_0 \to +\infty} \gamma_{i,i+1} = \frac{1}{\sum\limits_{k=1(k\neq i,i+1)}^{N} X_k(PL_{k,k+1}/PL_{k,i+1})} \qquad 1 \leq i \leq N-1. \quad (7)$$

The above equation indicates that, despite increasing the received power, the link efficiency remains entirely dependent on the path-loss ratio between the neighboring nodes and their corresponding further away nodes, which are not in contention with each other. Note that in the route discovery process, a multihop link is selected on the basis that only the next hop node should receive the signal at or above its sensitivity level. For further away nodes, this signal is expected to be received below the sensitivity level and, therefore, is classified as an interfering signal. The amount of interference from neighboring hopping nodes depends on the input data rate and the path-loss model.

The path loss is often modeled as a product of distance-dependent average path loss and lognormal variation in the local mean power level, i.e.,

$$PL_{i,i+1} = \left(D_{i,i+1}^{pl}\right)\left(10^{0.1\beta}\right)$$

or

$$\{PL_{i,i+1}\}_{dB} = 10.pl.\log(D_{i,i+1}) + \beta$$

where PL_{ii+1} is the path between two neighboring nodes at the distance $D_{i,i+1}$, β represents shadowing loss (in decibels) and is a Gaussian random variable with zero mean and standard deviations in decibels, and "pl" is the path-loss factor whose value depends on the propagation medium and antenna characteristics. For example, pl is normally in the range of two to four, where $pl = 2$ is for propagation in free space and $pl = 4$ is for severe path-loss environments. To investigate the effect of intrapath interference on the multihop link performance, we consider $pl = 2$ and $pl = 4$ in the absence of shadow fading ($\beta = 0$). The multihop link in our simulation model consists of nine IEEE 802.11b nodes with a bandwidth of 2 Mb/s, as shown in Fig. 1. In the absence of any interference, the received power is set to be just above the receiver sensitivity level (−93 dBm). Obviously, for the same received power, a higher transmit power is needed for $pl = 4$. The input data are generated at a constant bit rate (CBR) and then encapsulated into fixed 500 byte user datagram protocol packets. Tables 1 and 2 show the throughput performance of the multihop link at various CBR rates for $pl = 2$ and $pl = 4$, respectively. In these tables, we also list the interfering nodes affecting the communication link between the first and second

TABLE 1 Effect of Interfering Nodes on the First Link (Node 2 Reception) for $pl = 2$

Input Bit Rate	150K	175k	200k	225k	250k	275k	300k	325K	350k	375k	450k
Interfering nodes	N/A	8→2	8→2 7→2	7→2 6→2 8→2	6→2 7→2 8→2	6→2 5→2 7→2 8→2	5→2 6→2 7→2 8→2	5→2 6→2 7→2 8→2	4→2 5→2 6→2 7→2 8→2	4→2 5→2 6→2 7→2 8→2	4→2 3→2 6→2 5→2 7→2 8→2
Throughput %	99.90	82.7	48.0	36.3	22.7	12.4	5.12	0.92	0.07	0.00	0.00

TABLE 2 Effect of Interfering Nodes on the First Link for $pl = 4$ (b)

Input Bit Rate	275k	300k	325k	350k	375k	400K	450k	475k	500k	600k
Interfering nodes	N/A	N/A	4→2	4→2	4→2	4→2	4→2 3→2	3→2 4→2	3→2 4→2	3→2 4→2
Throughput %	99.91	99.87	91.81	60.10	50.48	49.93	49.91	49.89	49.88	48.81

nodes (i.e., first link in forward direction). It should be noted that interfering nodes in these tables have been listed in decreasing order of their relative impact on packet losses at node 2. We should also point out that the main reason for showing the impact of the interfering nodes on the first link is to signify that this link bears the highest traffic load and its packet losses would only reduce the load on the remaining communication links.

Looking at these tables, we can deduce that the highest throughput is achieved at low rates. This is because packets are generated at very low speed so that when a new packet arrives at the source node, its previously transmitted packet may have already reached a faraway node (or the destination node). Thus, under lower transmission rates, the relay nodes in proximity of node 2 are not involved in relaying packets and, thus, could not possibly interfere (fully or partially) with the reception of the current packet at node 2. However, at higher bit rates where packets are transmitted at faster rates, the probability of having more intrapath interference from a nearby relay would increase and thereby cause a significant reduction in the link throughput.

Based on the above observations, in the following we propose two multichannel strategies that aim at reducing the intrapath interference in multihop links.

A. Alternate Switching Channel System (ASCS)

Fig. 2 shows a very simple two-channel configuration system where a node receives and transmits packets in two frequency bands: B1 and B2. In this example, node *i* receives a packet in B2 (R: B2) but switches to B1 when operating in the transmission mode (T: B1). The frequency allocation of the next node (node i + 1) is reversed so that it receives packets in B1 (R: B1) but switches to B2 for transmission (T: B2). Under these conditions, the channel allocation pattern is repeated after every two nodes along a path from source to the destination. As will be discussed later, channel allocation for every node in an active link is determined in accordance with the node's number of hops to the destination.

Fig. 3 shows the throughput performance of the single-channel (SC) and the two-channel (2-CH) switching structures for a multihop link scenario (see Fig. 1) as a function of bit rates for $pl = 2$ and $pl = 4$. From this figure, we can see that since there is no interference at lower bit rates, the throughput remains at maximum (see also Table 1). As the bit rate increases, the possibility of interference from the neighboring nodes would also increase, thus causing the throughput to drop. On the other hand, the 2-CH systems, by eliminating some the interference from nearby nodes (operating in a different band), can offer a much better performance. For example, for $pl = 4$, where the transmit power attenuates more rapidly, the major source of intrapath interference is limited to fewer neighboring nodes (e.g., two hops away), which can be handled more effectively by the 2-CH structure. As for $pl = 2$, which corresponds to the free space propagation loss, the source of such interference extends well beyond a few neighboring nodes. This is why, even with the alternate switching channel system (ASCS), the throughput performance cannot be improved significantly due to the increased number of interfering nodes along the path (i.e., nodes using the same frequency channel). Thus, in order to better control the amount of intrapath interference, we have extended this approach by presenting a link partitioning scheme.

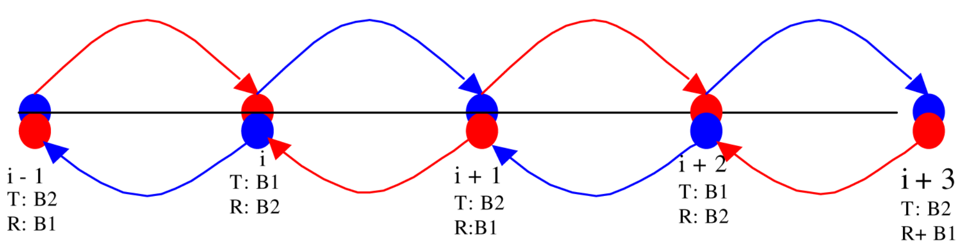

Fig. 2. ***Single NIC, half duplex, two channel switching system with systematic channel assignment for transmission and reception of data and acknowledgment (ACK) packets.***

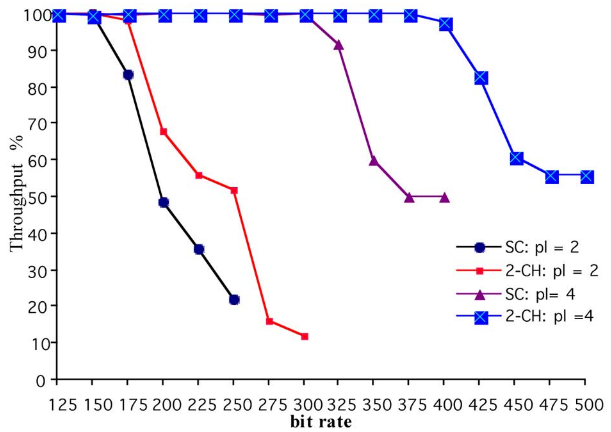

Fig. 3. *Performance comparisons between SC and switching 2-CH switching system for path-loss (pl) factor of 2 and 4.*

B. Link Partitioning

In this section, we introduce a more versatile scheme for multichannel transmission. The scheme is based on partitioning a multihop link where only nodes in the same partition use the same frequency channel. For connection between neighboring partitions, we design a half-duplex switching node, which will be referred to as a transitional node. The main attribute of the transitional node is its ability to sense the transmission medium in two bands (e.g., B1 or B2) so that it can switch to an appropriate channel whenever there is a packet to receive. In addition, in its transmission mode, it can switch between the two bands to send a packet in forward or reverse direction. Note that the transitional node is a border node between two neighboring partitions, where nodes in neighboring partitions do not use the same channel for communications. For better clarity, Fig. 4 shows a three-node example of a multihop link where node $i-1$ is forwarding data packets to the destination node $i+1$, via node i. In this example, nodes "$i-1$" and "$i+1$" are operating in their conventional single-channel mode (i.e., B2 and B1, respectively) whereas node "i" is instructed to switch to its transitional mode. Bear in mind that in this mode, node i can listen to both channels when the medium is idle. Thus, as indicated in Fig. 4, it can accept a data packet in B1 from node $i-1$ or switch to B2 to receive an acknowledgment from node $i+1$ (after sending a data packet to node $i+1$ in B2). In the transmission mode node i, depending on whether to send a packet in forward or reverse direction (e.g., acknowledgement packet), can switch between B2 and B1.

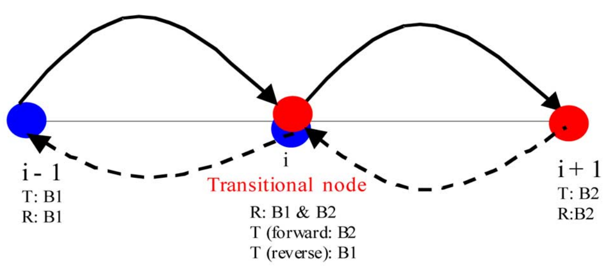

Fig. 4. *Partitioning of a multihop link via the proposed transitional node.*

We should emphasize that, in this multichannel system, nodes normally operate in the conventional (default) single-channel frequency band (e.g., B1 or B2). However, if instructed, they would be able to switch to transitional mode. The decision as to which node should switch to the transitional mode (e.g., B1-to-B2 or B2-to-B1) comes from the routing layer, which will be discussed in more detail later.

Fig. 5 shows a number of configurations that uses different size partitions of the nine-node multihop link depicted in Fig. 1. For example, in Fig. 5(a), the link is partitioned into two sectors via only one transitional node. In the other configurations (b)–(d), the link is divided into more partitions. We note that configuration (d) has a similar structure as the 2-CH alternate switching system described earlier (see Fig. 2).

We assessed the effect of intrapath interference on the throughput performance using the same path-loss factors as before (i.e., $pl=2$ and $pl=4$). We should point out again that the transmit power in both cases had to be adjusted so that the received power would be the same for every node along the path. Figs. 6 and 7 show the throughput performance as a function of the bit rate for all the configurations depicted in Fig. 5. We can observe that while configuration (a) offers the best throughput results for $pl=2$ (see Fig. 6), it also produces the worse performance in the case of $pl=4$ (see Fig. 7). This is because at $pl=4$, the transmit signal decays at a much faster pace and, thus, nodes in the neighboring partitions (e.g., same channel) are too far away to interfere from each other. It is for the same reason that configuration (d), which has the smallest partition size (one hop), by blocking any interference from two hops away nodes produces the best results. This is then followed by configurations (b), (c), and then (d), which is in accordance with the increasing order of their partitions size (see Fig. 7). At the same time for $pl=2$, the interference may spread well over a few neighboring nodes and include some interfering nodes from different partitions. In other words, under less severe propagation environments, the source of interference is not only limited to nodes in the same partititon (intrapartititon interference) but also from nodes in the same-channel neighboring partititons (interpartititon interference). That is why configuration (a), which is free from any interpartititon interference, produces the best performance in the case of $pl=2$.

Based on the above observation, it becomes clear that, for a given channel propagation model, the size of each partition can play a crucial role in controlling both

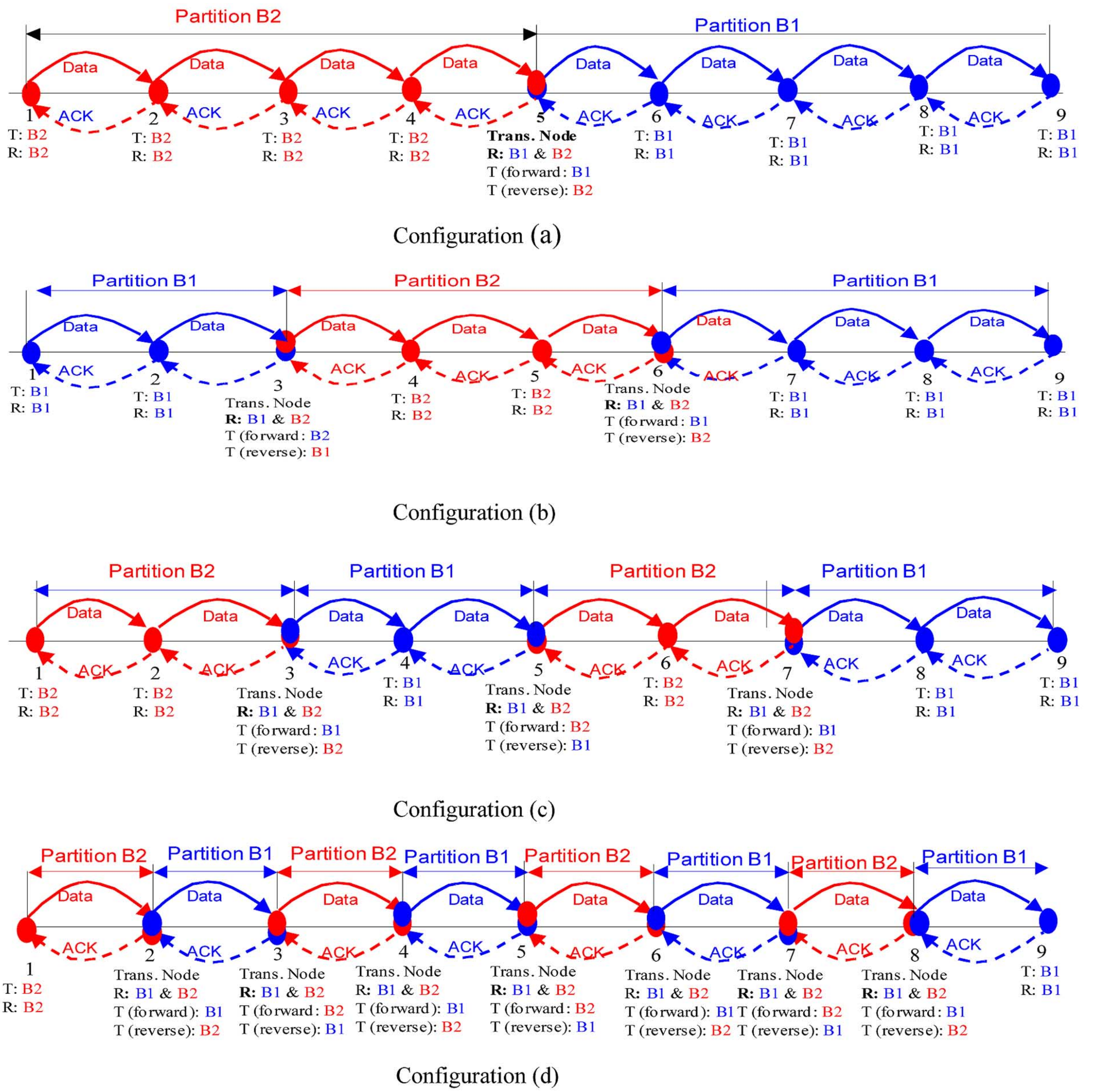

Fig. 5. ***Two-channel link partitioning: configurations (a)–(c).***

intra- and interpartition interference. To minimize the intrapartition interference, the size of each partition should be kept as small as possible, but at the same time it should be large enough to provide a sufficient gap between the two neighboring partitions of the same frequency band. It is also important to note that the amount of inter- and intrapartition interference also depends on the data transmission bit rates. For instance, as the data rate increases, the interpartition interference is the first source of interference. However, as the bit rate increases further, the intrapartition interference will then be added, which, together with the interpartition interference, can cause a sharp drop in the throughput performance.

C. Three-Channel Extension

In the previous section, we observed that a smaller size partition could effectively reduce the intrapartition interference, but this would be at the expense of reducing the distance between two neighboring partitions (same channel). Bear in mind that a shorter distance between the interfering partitions could result in an increase in the interpartition interference, especially under less severe path-loss environments. Obviously, by utilizing more nonoverlapping frequency bands, we should be able to effectively control the size and distance between the interfering partitions. Based on the same strategy, such an extension is rather straightforward. It uses the same transitional node

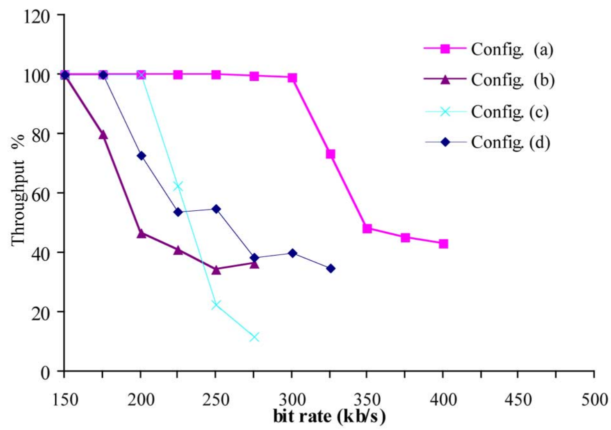

Fig. 6. ***Throughput performance of the two-channel systems corresponding to configurations (a)–(c) in Fig. 3 for path-loss factor of*** $pl = 2$.

in order to allow switching between two nonoverlapping bands. As an example; Fig. 8 illustrates two configurations of the same multihop link (see Fig. 1). Configurations (a) and (b) in this figure correspond to the partition size of three-hop and two-hop, respectively.

Both configurations have been used to assess the performance of the three-channel structures. Fig. 9 shows their throughput performance with path-loss factors of $pl = 2$, and $pl = 4$. As expected, the three-channel (3-CH) extension, compared with the 2-CH system (see Figs. 6 and 7), can considerably improve the link performance. We note that with $pl = 4$, the configuration (b) can effectively suppress both interpartition and intrapartition interferences. In the case of $pl = 2$, the interpath interference can still remain a limiting factor. This indicates that, under less severe propagation environments, utilizing more nonoverlapping channels would be required. However, in our experiments utilizing a link consisting of a higher number of nodes, we observed that the proposed link partition approach does not require too many nonoverlapping channels in order to effectively eliminate the interference. Bear in mind that the main objective of deploying more channels is not only to reduce the size of each partition (reducing the intrapartition interference) but also to allow a larger gap between the interfering partitions and, therefore, reduce the interpartition interference.

D. RTC/CTS Mechanism in MultiChannel Link Partitioning

In IEEE 802.11b [1], for example, the optional request-to-send (RTS) and clear-to-send (CTS) provides handshaking control over the CSMA/CA environment, which aims at minimizing collisions among hidden nodes. This occurs when two nodes that do not sense each other attempt to send a packet to the third node, which is within their transmission reach. Consequently, this situation can cause both packets to collide and, thus, prevent either packet from being delivered successfully at the third node. In the case of a link partitioning scheme, the hidden terminal problem obviously exists within each partition, as shown in the example depicted in Fig. 10.

In this example, nodes $i - 4$ and $i - 2$ cannot hear each other and their packets could collide at the access node $i - 3$. However, in the vicinity of the transitional node, the neighboring nodes (i.e., $i - 1$ and $i + 1$) do not use the same

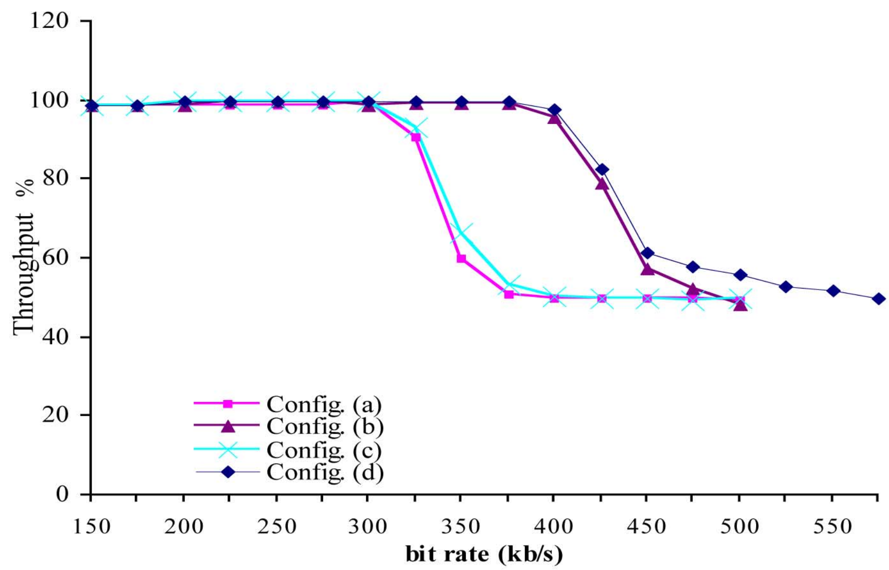

Fig. 7. ***Throughput performance of the two-channel systems corresponding to configurations (a)–(d) in Fig. 3 for propagation factor of*** $pl = 4$.

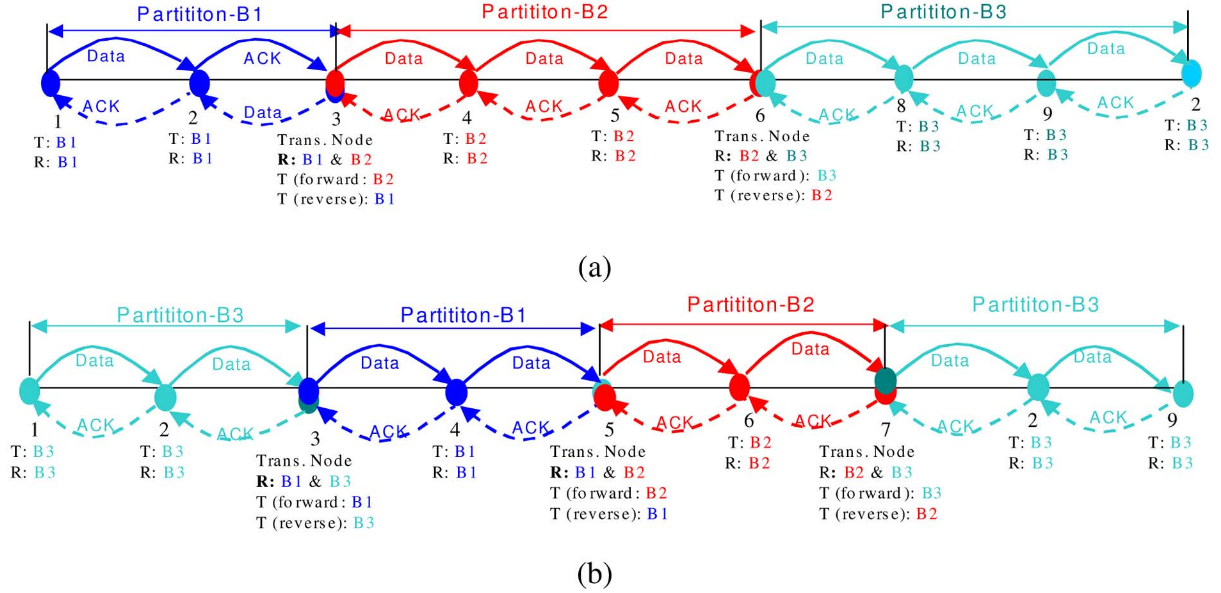

Fig. 8. ***Three-channel partitioning systems: (a) two-hop and (b) three-hop configuration.***

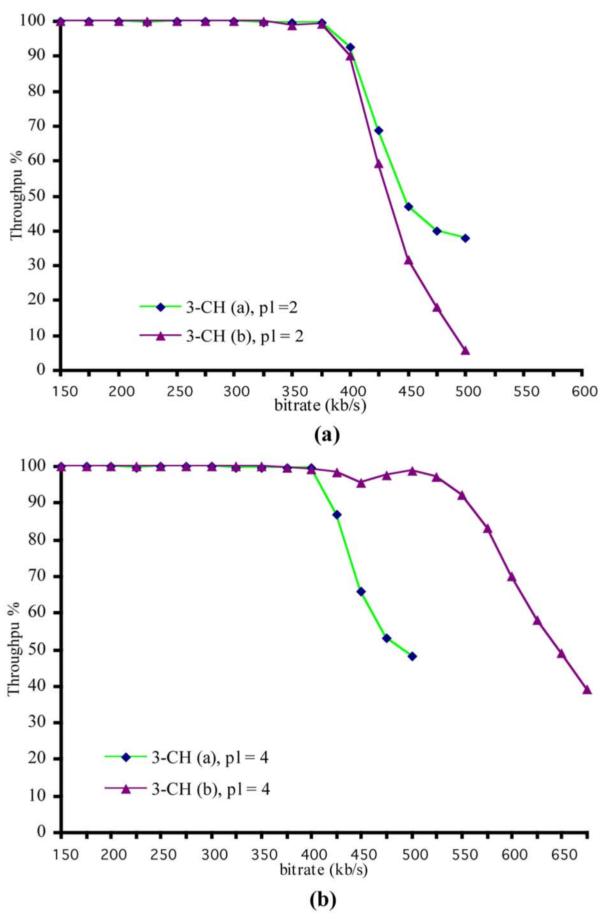

Fig. 9. ***Throughput performance of the 3-CH system corresponding to configurations (a) and (b). (a)*** $pl = 2$ ***and (b)*** $pl = 4$.

frequency band. Here, the transitional node i, although capable of hearing both channels (when the medium if free), can only switch to one of the channels to receive a packet. In other words, there would be no collision, but the transitional node i can only receive one of the packets.

Keep in mind that the medium reservation via the RTS/CTS handshaking can solve the hidden terminal problem, but this would be at the expense of extra overhead. The additional overhead is mainly because a node (e.g., node $i-4$ in Fig. 10) prior to transmitting a data packet will first send an RTS packet to its next hop destination node. By sending a CTS reply, this node can pave the way for receiving a data packet without fear of collision. Regarding the proposed multichannel scheme, RTS/CTS can play the same handshaking role within each partition.

Fig. 11 shows the throughput performance comparison of single-channel and two-channel partitioning with and without the RTS/CTS option. For the sake of simplicity, we only use configuration (a), which offers the best performance for $pl = 2$ (see Fig. 6). Looking at these results, we can see that the RTS/CTS mechanism can have an adverse impact on the throughput performance. Indeed, as the bit rate increases, the transmission of the RTS/CTS frames would also increase. We can also observe that by increasing the number of maximum retransmissions, the RTS/CTS remains ineffective as far as improving the throughput is concerned.

E. Route Discovery and Data Transmission

In this section, we are mainly concerned with the ad hoc routing aspects of the multichannel schemes and, particularly, the way in which every node along the path is

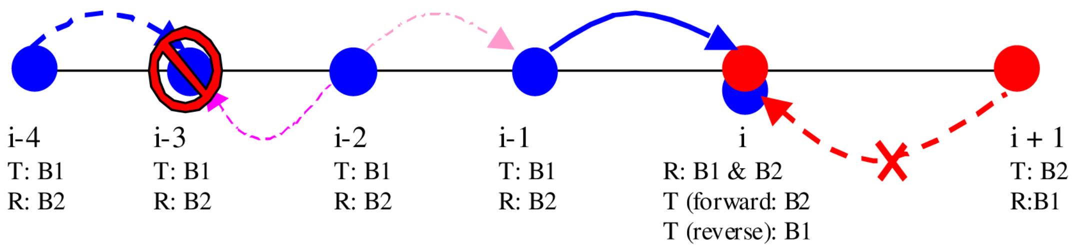

Fig. 10. ***Hidden node effect in link partitioning.***

assigned to a specific frequency band. In this respect, we have considered the AODV routing protocol [7].

In the route discovery phase, which includes initiating RREQ and RREP packets, all the nodes operate initially in a single channel—e.g., B1—in search of a route from source to destination. As soon as a route is established, each node along the path will know the hop count to the destination. Bear in mind that in the AODV protocol, the hop-count information is attainable from the routing table. This information is then used to assign an appropriate frequency band to each node along the newly established path.

In the case of ASCS, nodes with an odd hop count to the destination node are assigned to B1 for transmitting packets (transmission mode) and B2 for receiving packets (receiving mode). Similarly, nodes with an even hop count will adjust their transmission frequency at B2 and reception at B1. In this case, a node uses the same frequency band for transmission of data and ACK packets.

For the 2-CH partitioning approach, as shown in Fig. 5, a link can be divided into partitions where nodes in neighboring partitions will be assigned to different nonoverlapping frequency bands. For example; defining j as the number of hops in each partition, configurations (a)–(d) in Fig. 5 correspond to $j = 4$, $j = 3$, $j = 2$, and $j = 1$, respectively. For a partition size of j hops, the channel allocation, based on each node's hop count (accessible from the AODV routing layer), can be arranged by first defining

$$D = \{I, M\}$$

where

$$I = \mathrm{Int}\left\{\frac{\text{hop count}}{j}\right\}$$

and

$$M = \mathrm{Mod}\left\{\frac{\text{hop count}}{j}\right\}.$$

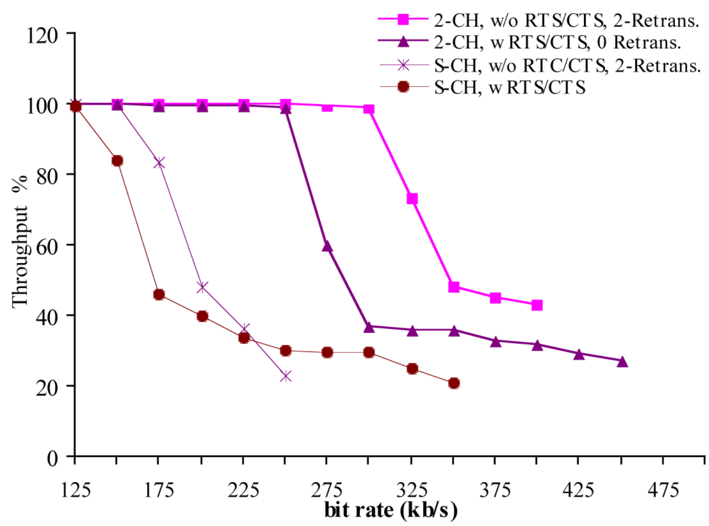

Fig. 11. ***RTS/CTS effects on single-channel and 2-CH partitioning [configuration (a) with*** $pl = 2$***].***

In the above, Int{.} represents the integer part of division and Mod{.} is defined as unsigned modulus function (unsigned remainder after division).

To set an appropriate mode of operation to every node along the path, the values of the first and second term in $D\{.,.\}$ will be used for channel allocation. For example, for $k = 0, 1, 2, \ldots$

$$\text{If } \begin{cases} I = 2k \\ M = 0 \end{cases} \quad \text{A node switches to its transitional mode : B1} \leftrightarrow \text{B2}$$

and for

$$\begin{cases} I = 2k \\ M = 1, 2, ., ., j-1 \end{cases} \quad \text{A node is a B1 node.}$$

Otherwise

$$\text{If } \begin{cases} I = 2k+1 \\ M = 0 \end{cases} \quad \text{A node switches to its transitional mode: B2} \leftrightarrow \text{B1}$$

and for

$$\begin{cases} I = 2k+1 \\ M = 1, 2, ., ., j-1 \end{cases} \quad \text{A node is a B2 node.}$$

For a 3-CH system, Fig. 8 shows two examples with partition sizes $j = 3$ and $j = 2$ that use three nonoverlapping bands: B1, B2, and B3. In order to ensure the longest possible distance between the same channel partitions, 3-CH would only require three types of transitional nodes, e.g., B1-to-B2, B2-to-B3, and B3-to-B1. Thus, in a similar arrangement described above, any node along the path will be assigned to an appropriate operational mode according to the first and second terms in $D\{.,.\}$. For $k = 0, 1, 2, 3 \ldots$

$$\text{If } \begin{cases} T = 3k+2 \\ M = 0 \end{cases} \quad \text{a node is the transition nod, e.g., B1} \leftrightarrow \text{B2.}$$

In this case, all the $j-1$ preceding nodes, i.e.,

$$\begin{cases} T = 3k+2 \\ M = 1, 2, ., ., j-1 \end{cases} \quad \text{will be assigned to B1.}$$

Similarly

$$\text{If } \begin{cases} T = 3k+1 \\ M = 0 \end{cases} \quad \text{a node is the transition nod, e.g., B2} \leftrightarrow \text{B3}$$

and all its $j-1$ preceding nodes will be assigned to B2 as shown below

$$\begin{cases} T = 3k+1 \\ M = 1, 2, ., ., j-1 \end{cases} \quad \text{will be assigned to B2.}$$

Finally

$$\text{If } \begin{cases} T = 3k \\ M = 0 \end{cases} \quad \text{a node is the transition nod, e.g., B3} \leftrightarrow \text{B1}$$

and all its $j-1$ preceding nodes

$$\begin{cases} T = 3k \\ M = 1, 2, ., ., j-1 \end{cases} \quad \text{will be assigned to B3.}$$

It should be noted that in this arrangement, the first node and the last node in a link do not need to operate in a transitional mode, even if they are selected as one. In addition, depending on the number of nodes in the link, the first partition in the path may be of a smaller size [see Fig. 5(b) for 2-CH and Fig. 8(a) for 3-CH]. We should point out that this proposed multichannel channel allocation method can be easily extended to include more nonoverlapping channels.

F. Route Maintenance

If a node along the path detects a route breakage to the next hop node, it will send a RERR to the source node based on the channel that is allocated to every node for transmitting a packet in reverse direction (see Figs. 5 and 8). As soon as the route is declared broken, all nodes will switch back to a single frequency band system (i.e., B1). The source node will then originate a new RREQ using this channel in order to find a new route. Once the new route is established, the channel allocation for every node begins via the MAC layer, based on the node's hop count to the destination.

Finally, we should emphasize that the main thrust of the proposed partitioning scheme is to minimize the amount of intrapath interference as soon as a multihop link has been established for data traffic. Nonetheless, in mobile ad hoc network environments, a link may have to be rediscovered from time to time, and this process can cause a long delay [39]. However, a combination of multiple-path routing and multiple-description coding may improve the ad hoc routing performance under mobility conditions. Therefore, in the next section, we investigate the application of a multichannel strategy for multiple-path routing in order to eliminate the effect of interference between the multiple routes (interpath interference).

IV. MULTIPLE-PATH MULTICHANNEL ROUTING

In the previous section, we described a multichannel routing strategy aimed at improving the multihop link performance in a single-path route from source to destination. In this section, our objective is to tackle another major obstacle in supporting real-time traffic, which is the long delays associated with frequent route changes due to the dynamically changing network topology. This includes latency in detecting a link loss as well as the time needed to discover a new route. A viable method to reduce the probability of losing a link is to use a multiple-routing approach, which has been extensively studied in recent years [26]–[36]. Indeed, one of the criteria in designing a multiple routing protocol is to increase the possibility of having at least one route from the source to the destination, particularly in the case of continuous media communications. On this basis, [33] presents a method where only one route is primarily used and alternate routes are utilized when this route is broken. Since this approach is based on a single stream transmission, it can still suffer from the delay associated with detection of a link loss.

For multiple-path routing with simultaneously transmitted packets, split multiple-path routing (SMR) has been proposed in [36], which focuses on building and maintaining maximally disjointed paths. It should be noted that the selected multiple routes may share some of the nodes (joint nodes) along their paths to the destination. This not only would cause congestion but may also prevent utilizing network resources most efficiently. The SMR protocol is based on DSR and the traffic load is distributed in two routes. Analytical results in [37] reveal that, in comparison with a general single-path routing protocol, a split multiple-path routing mechanism can provide better performance in terms of congestion and capacity. However, in this paper, the effect of cochannel interference between different paths has not been taken into consideration. Bear in mind that even in the absence of any joint nodes, multiple routes from source to destination are normally within the interference range of each other. Obviously, this can significantly deteriorate the end-to-end communication performance. On the other hand, if each route can operate in different frequency bands, the effect of cochannel interference can be eliminated [26].

Therefore, here we are mainly concerned with evaluating the performance of dual-band/dual-path networks for video traffic. In particular, we are interested in reducing the possibility of losing both routes at the same time, which could otherwise have a significant impact on the recovery of video. In the following, we present the details of this dual-band DSR-based protocol. Since the protocol is primarily designed for transmission of MDC data packets, we use an MPEG-4 based dual-description video-coding scheme to evaluate the multiband/multiple-path routing protocols and compare it with the SMR protocol.

A. Dual-Channel/Dual-Path Routing (DDR)

Let us assume that every node can be assigned to two different nonoverlapping frequency bands B1 and B2 where the channel assignment is controlled by the MAC layer. For the ad hoc routing protocol, we have considered DSR [8]. This protocol with its inherent routing structure can be easily extended for multiple-path diversity routing.

For instance, in DSR, when a source node originates a new data packet addressed to the destination node, the source node will insert a source route in the header of the packet, which gives the sequence of hops from the source to the destination. Normally, the sender will obtain a suitable source route by searching its "route cache." If no route is found in its cache, it will initiate the route discovery to find a new route to the destination [8].

To initiate the route discovery, the source node will broadcast the RREQ packet in order to find paths to the destination. Each RREQ identifies the source and destination of the route discovery, which contains a unique request identification (ID). Each RREQ also contains a record listing the address of each intermediate node through which this particular copy of the RREQ has been forwarded.

When another node receives this RREQ and is the destination of the route discovery, it returns an RREP to the source of the route discovery. Otherwise, it will check if this RREQ is duplicated or not by the ID. If it is not the duplicate, it appends its ID and rebroadcasts the packet. Otherwise, it will discard this duplicate RREQ.

It should be noted that it is very likely that good routes will be dropped if we drop all the duplicate RREQs [36]. An example of a two-band routing system is shown in Fig. 12. As can be observed, we may only get the routes of S-1-4-D and S-3-2-D. Routes S-1-2-D and S-3-4-D will be discarded because of the duplicate RREQ. In order to avoid discarding good routes from the source to the destination, in this protocol we modify the transmission schemes of the RREQ compared with DSR. For example, instead of discarding every duplicate RREQ, intermediate nodes will forward the RREQ whose hop count is not bigger than that of the first received RREQ, even if they have the same ID. In this way, the source node may obtain all possible routes to the destinations [26].

An example of a DDR routing protocol is shown in Fig. 13, where the source node will select the two best routes from the route cache for data transmission at B1 and B2. In this protocol, all the nodes can listen to both frequency bands B1 and B2. Let us assume that the source node initially sends the RREQ in band B1. The other nodes will then use the same band to broadcast the RREQ and to send the RREP. When the source node receives all the RREPs, it will obtain

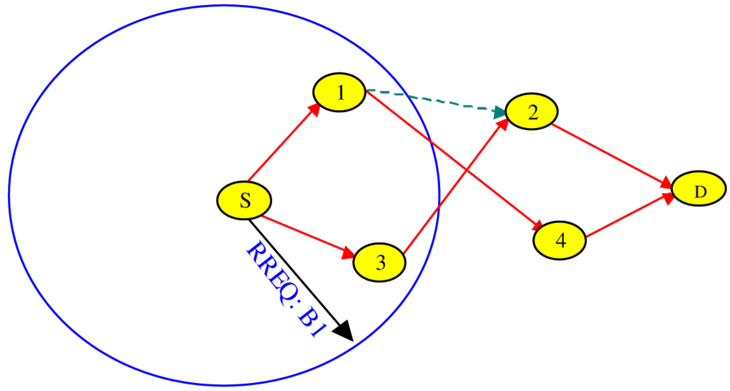

Fig. 12. *Route discovery process.*

multiple routes to the destination, which are stored in the route cache. However, it is possible that there would be too many potential routes from the source to the destination, particularly when the node density is high.

In order to avoid excessive overhead, we set a threshold in the destination node in such a way that if the number of RREQs received by the destination is smaller than this threshold (e.g., ten), the destination will send an RREP. Otherwise, the destination will discard this RREQ.

To measure the performance of each route for the selection process, we use the following metrics.

a) Hop count.

b) Power budget: the total power loss when transmitting a packet from the source node to the destination, which is defined as [38]

$$\text{Power Budget} = \sum_{i=1}^{N-1} PL_{i,i+1}$$

where $PL_{i,i+1}$ is the power loss between nodes i and $i+1$, N is the hop-count of this route, *PowerBudget* is the total power loss of this route.

c) Number of joint nodes between two routes.

In this protocol, we insert the power budget into the routing entry. To carry the power loss information, we use the reserved bits of the RREP. The process begins from a node located one hop away from the destination node. When this node receives the RREP from the destination, it first calculates the power loss $(PL_{N-1,N})$ from the destination based on the transmitting power and receiving power and appends it into the route entry. Then it will send this power loss information to the next node in the direction of the source. The receiving node then calculates the new power loss $(PL_{N-2,N-1})$ between these two nodes and adds it to the previous power loss $(PL_{N-1,N})$ from the RREP. After that, it will send the new total power loss $(\sum_{i=N-2}^{N-1} PL_{i,i+1})$ to the next node in the reverse direction

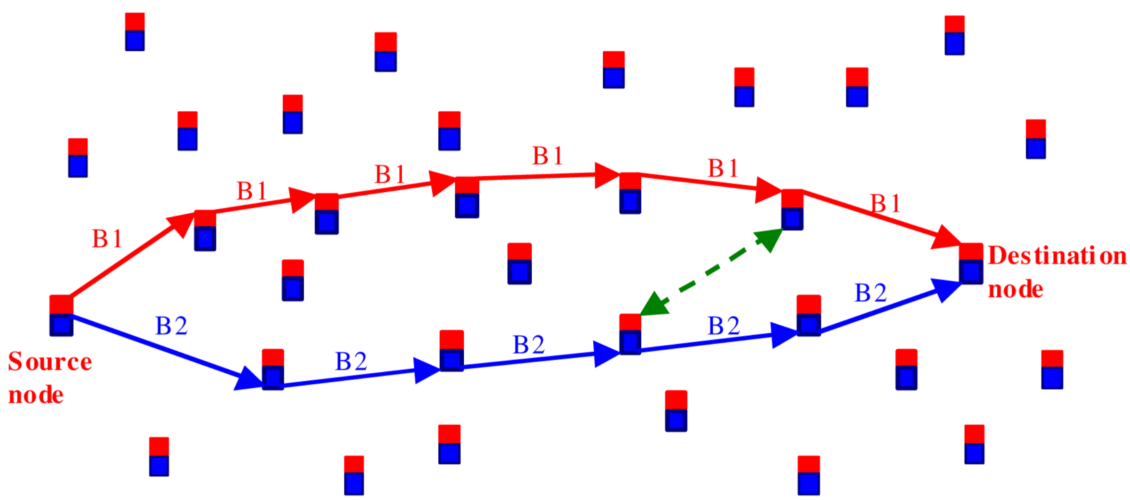

Fig. 13. *DDR protocol.*

with the RREP. This process continues until reaching the source node. In this way, we can obtain the power budget for this route. We should point out that, to avoid the complexities involved in the implementation of the power-budget metric, we can use the route acquisition latency metric [36]. For example; in this metric, the shortest delay route is the one through which the destination node receives the first RREQ.

1) Multiple Route Selection: In the route selection process, the source node will try to find the two best routes based on the above metrics. First, a route with the smallest hop count has the highest priority (metric a). If two or more routes have the same hop count, then the power budget (metric b) is used to select the route with the lowest power loss.

The next step is choosing the second best route amongst the remaining routes. In this case, the priority is given to a route with a minimal hop count. However, if two or more routes have the same minimal hop count, we will consider the number of joint nodes between the current route and the first best route. The route with smallest number of joint nodes will be selected as the second best route. In the case where there are more routes with the same number of joint nodes, the route with the minimal power budget will be selected.

We should point out that although joined nodes may not seem to have any major impact on the dual-channel protocol's performance as far as interference is concerned, under mobility conditions it reduces the possibility of losing both routes at the same time. Bear in mind that maintaining at least one route would be a crucial factor for real-time video applications.

2) Data Packet Transmission: After the source selects the two best routes, two data streams will be sent to the destination along these two routes in different bands: B1 or B2 as shown in Fig. 13. After the intermediate node receives the data stream, it will relay the data packet according to the sequence of hops stored in the header of the packet. The data packet will be transmitted in the band in which this packet is received.

3) Route Maintenance: Normally, a route can be disconnected because of mobility or packet collision. In this protocol, when one node detects a broken link, it will send the RERR packet. Once the source node receives the RRER packet, it will remove every route entry in the route cache, which uses the broken link. Under this condition, the source node will assess how many active routes are left in the route cache to the destination using the following steps.

- If there is more than one active route left in the route cache, the source node will select the two best routes (i.e., among the leftover routes) according to the rules mentioned above. The data packet will be transmitted with these two routes each using a different frequency channel.
- If there is only one route left, the source node will continue using it while initiating a new RREQ at a different channel. The source node will then append all the newly discovered routes, which may include the existing active route, into the route cache. Finally, the source node will select the two best routes in the route cache for data transmission.
- If there is no route left, the source node will initiate a new RREQ at band B1 (or B2). Then the source node begins a new route discovery process as discussed before.

B. Dual Description Video Coding

The performance of the proposed dual-path routing scheme for real-time video applications can best be evaluated using dual description video coding. Bear in mind that the basic principle of MDC is to encode a source into two (or more) bitstreams, such that a high-quality reconstruction is achieved when both (all) bitstreams are received successfully. On the other hand, a lower but still acceptable quality reconstruction can be accomplished in the presence of only one bitstream. To satisfy these requirements, it is essential to introduce correlations between the two descriptions such that if one of the descriptions is lost, it can be estimated from the other. Introducing correlations would consequently result in expanding the source bandwidth. This can only be justified if multiple routes route from source to destination do not always endure the same losses at the same time. However, this depends on the network's ability to provide multiple reliable routes. In addition, any improvement in the service quality should not ignore the effect of increased traffic load on the network. Optimizing tradeoffs between network resources, bandwidth expansions, and distortion are the most challenging aspects of MDC/multiple-path routing and are beyond the scope of this paper.

As far as the coding aspects of MDC are concerned, there have been extensive works in the past several years [40]–[51]. For image communications, [44] presents an MDC scheme that uses pairwise transforms to introduce a controlled amount of correlation (and hence, redundancy) between the two bitstreams with the objective of improving the image quality when only a single description (SD) is received. This general framework claims to yield acceptable images from a single description with only a small amount of redundancy. Other image-coding schemes have also been proposed in literature, including overcomplete frame expansions [46], wavelet, and subband coding [47]. In the case of video in particular, it is more than just applying an MD image coder to the prediction error signal. The main difficulty with motion-compensated interframe coded video is the effect of a distortion propagation phenomena, which is due to a mismatch between the encoding and decoding loops. For instance, the use of multiple coding modes and redundancy allocation among the descriptions is investigated in [48]–[50]. In [51], a mismatch, due to

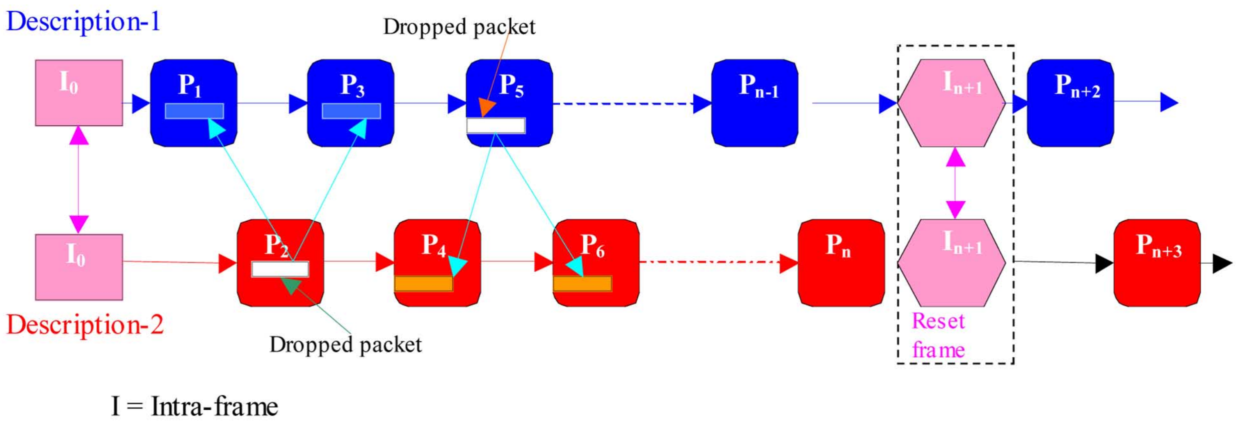

Fig. 14. *Temporal-based dual description coding with packet concealment arrangements.*

motion compensation, has been taken into consideration by interlacing high- and low-quality coded frames to produce two bitstreams where a loss of one description does not affect the other.

Here, however, we are mainly concerned with evaluating the performance of the proposed multiple routing protocol for video applications. In this respect, we have implemented a simple temporal-based dual description coding (TDDC). In the TDDC scheme, odd and even indexed frames are encoded separately using motion-compensated interframe coding. Under these conditions, each coded prediction frame (P-frame) will depend on the earlier P-frames and if one description is entirely lost, the frame rate will be reduced. The operation of the TDDC can best be described by looking at Fig. 14. As illustrated, the same INTRA coded frame (i.e., frame I_0) is used for both descriptions. In addition, the INTRA reset can be applied to prevent propagation of distortion in either description.

In this figure, we have also shown the packet-loss concealment arrangement. The decoder interpolates the missing information using the colocated pixel values from the nearest frames, which are transported via the other description (see Fig. 14). This simple concealment arrangement can be very effective if both routes do not suffer link breakage around the same time.

For the sake of comparison, we have also considered a so-called duplicate transmission coder (DTC), where the video is encoded in a single description and then each coded packet is transmitted via both routes. For the DTC, as shown in Fig. 15, the concealment process consists of two distinct cases: Case 1 assumes that packet drops within the *n*th frame of the first and second description are not colocated. In this case, the corresponding decoded packets in the *n*th frame of one description are utilized to fill in the missing area in the other description. Case 2 is mainly concerned with a more undesirable situation, where the same packets have been dropped in both routes. Under this condition, we can estimate the missing information using, for instance, the directional interpolation presented in [52].

C. Performance Evaluations

In this section, we access the performance of video transmission over ad hoc networks using a combination of the TDDC and the DDR protocol. For the sake of comparison, we also use the single-channel SMR protocol, as well as the duplicate coder. Both the TDDC and DTC schemes are implemented using the MPEG-4 verification model (without B frame option).[1] The average bit rate for each description is 320 kb/s. We use two test sequences: "Foreman" (QCIF, 15 fps, and 100 frames) and "Coastguard" (QCIF, 15 fps, and 100 frames). As mentioned earlier, the TDDC technique uses the same INTRA coded frame (i.e., frame 0) for both descriptions. For the remaining frames, the odd-indexed frames and the even-indexed frames are independently encoded for transmission over route 1 and route 2, respectively.

In our mobile ad hoc test scenario, nodes are placed in a rectangular field (400×1500 m^2) and move randomly. The mobility model uses the random waypoint model [53]. The number of nodes was varied to change node density. As before, in the physical layer, the transmission power is 10 dBm, the receiver sensitivity is -93.0 dBm, the IEEE 802.11b data rate is 2 Mb/s, the noise factor is 10.0, and the path-loss factor is $pl = 2$ (free space).

In the simulations, we use the following metrics to evaluate the performance.

1) PTwoRoutes is the probability of having two reliable routes simultaneously from the source to the destination. It is defined as

$$\text{PTwoRoutes} = \frac{\text{numWithTwoRoutes}}{\text{numSent}} \times 100\%$$

[1]All documents related to JVT (H.264 & MPEG-4 Part 10): ftp://ftp.imtc-files.org.

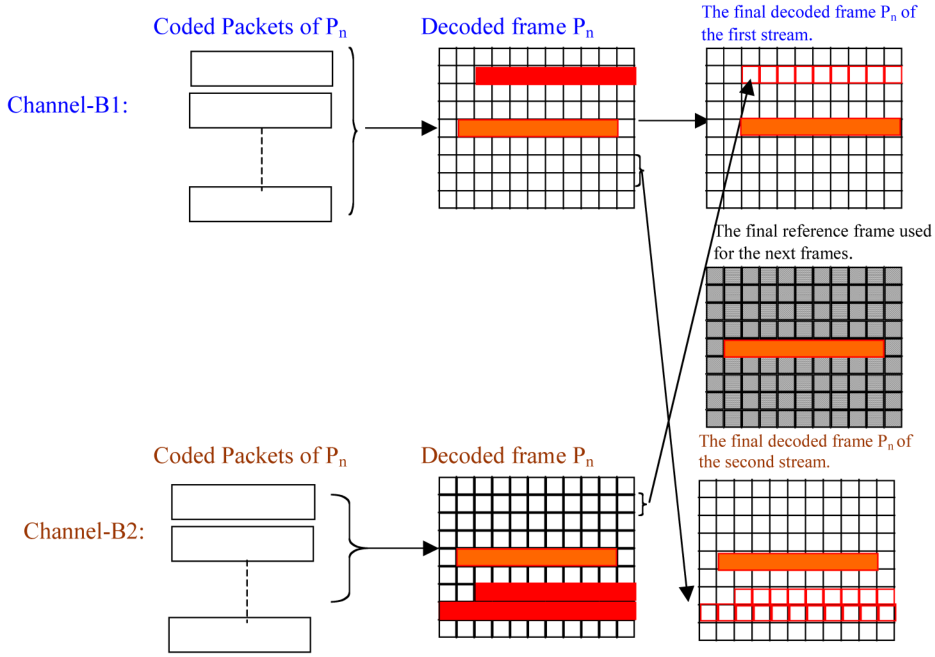

Fig. 15. ***Bitstream combiner for packet-loss recovery in duplicate decoder.***

where "numWithTwoRoutes" is the number of packets received at the destination via both routes and "numSent" is the number of sent packets by the source. It should be noted that PtwoRoutes can also represent the throughput performance.

2) POneRoute is the probability of having at least one reliable route from the source to the destination. It is defined as

$$\text{POneRoute} = \frac{\text{numWithOneRoute}}{\text{numSent}} \times 100\%$$

where "numWithOneRoutes" is the number of video packets, which are received with either route by the destination.

Fig. 16 shows the throughput comparison between two schemes in a network consisting of ten nodes and packet sizes of 300, 350, 400, 450, and 500 bytes. As can be observed in all three cases, by eliminating interpath interference, the DDR can overwhelmingly outperform the single-channel SMR. We have also compared the results of both schemes for networks of differing numbers of nodes. As shown in Fig. 17, for a packet size of 500 bytes, the DDR results, compared with SMR, verify the profound

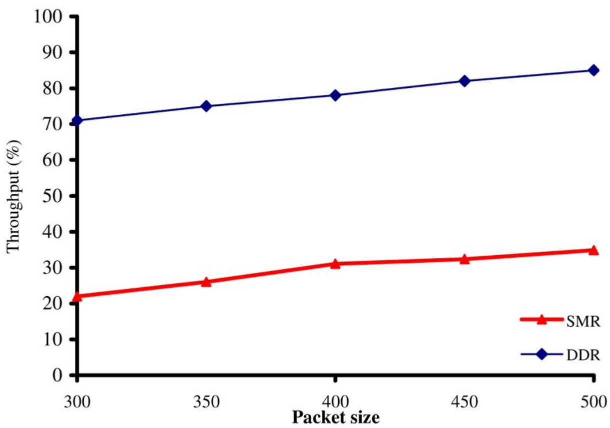

Fig. 16. ***Throughput comparisons between two schemes with different packet sizes.***

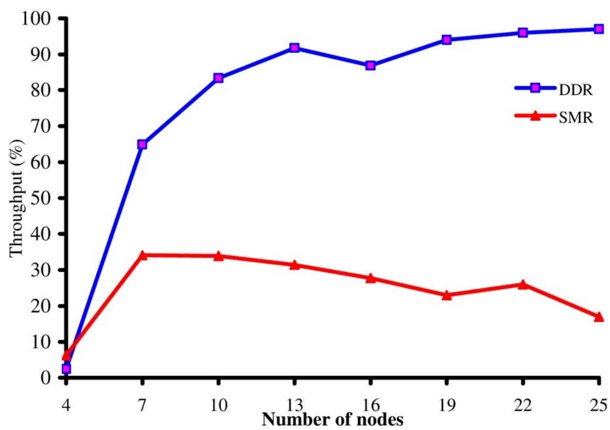

Fig. 17. ***Throughput comparisons between two schemes with different numbers of nodes.***

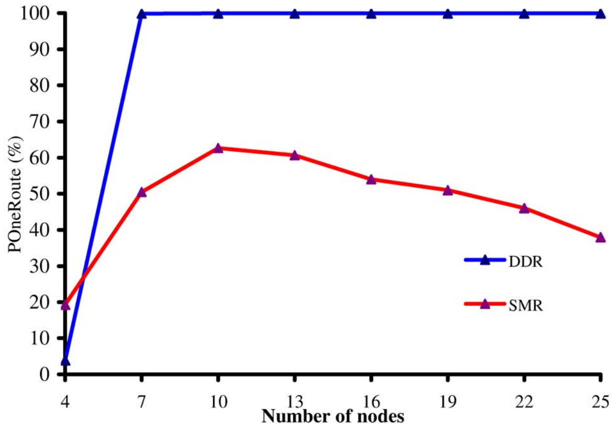

Fig. 18. ***The comparisons of probability of having at least one route with different numbers of nodes.***

effect that the elimination of inter-path interference can have on the multiple-path routing performance.

We should point out that in this experiment, we made sure that the highest throughput could be achieved in the absence of any interpath interference and 100% connectivity of both routes. However, under mobility conditions, maintaining their connectivity at the same time is not very likely and often link breakages may occur. This could cause a substantial loss of packets. In this respect, the multiple-path routing approach has a clear advantage over conventional single-path routing by providing better link connectivity even though all the multiple routes may not be available at all time. To further elaborate on this important feature, Fig. 18 shows the comparison between SMR and DDR in terms of the probability of having at least one route from the source to the destination with a different number of nodes in the network. From this figure, we can clearly observe that DDR, by eliminating the inter-path interference—particularly at the higher nodes' density—can indeed provide a far more robust transmission of video packets than SMR.

In terms of video quality, Figs. 19 and 20 show the peak signal-to-noise ratio (PSNR) quality of video signals at the destination node for 200 frames of "Foreman" and 150 frames of "Coastguard." In these experiments, TDDC or DTC is used to generate the video packets in two descriptions. The source node then transmits them to the destination using either DDR or SMR protocols. As can be observed, a significant gain in PSNR can be accomplished using the DDR protocol. Such a significant gain is mainly due to the fact that DDR improves the link connectivity under mobility conditions, which is an essential factor for transmission of real-time traffic over mobile ad hoc networks.

V. CONCLUSION

In a point-to-point multihop communication, a number of nodes may participate in relaying a long stream of packets from source to destination. For continuous media applications, this could severely limit the throughput performance of the ad hoc nodes. In this situation, the

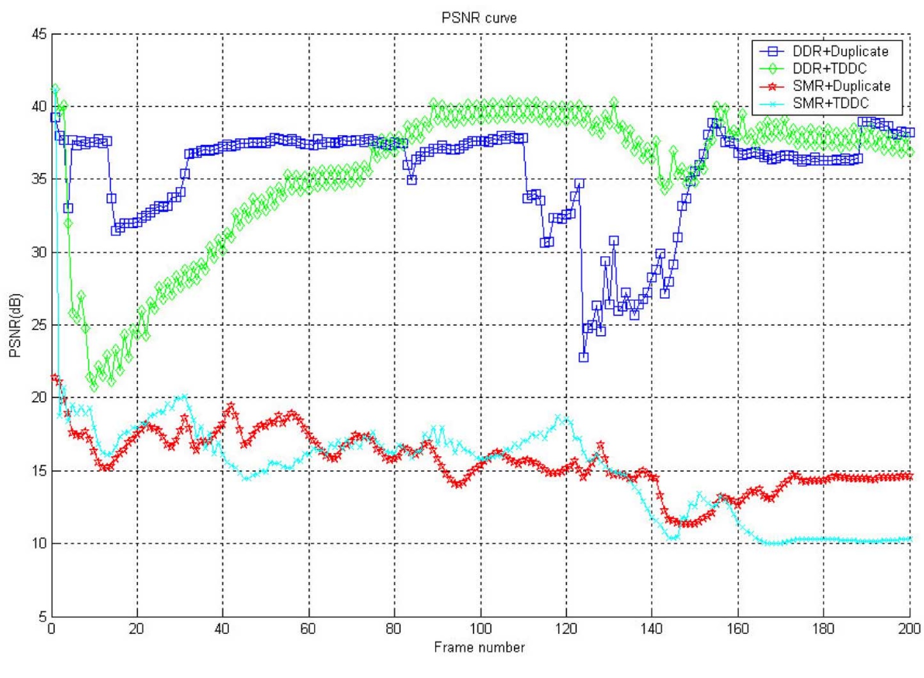

Fig. 19. ***Objective quality comparison of different encoders using different routing protocols: "Foreman."***

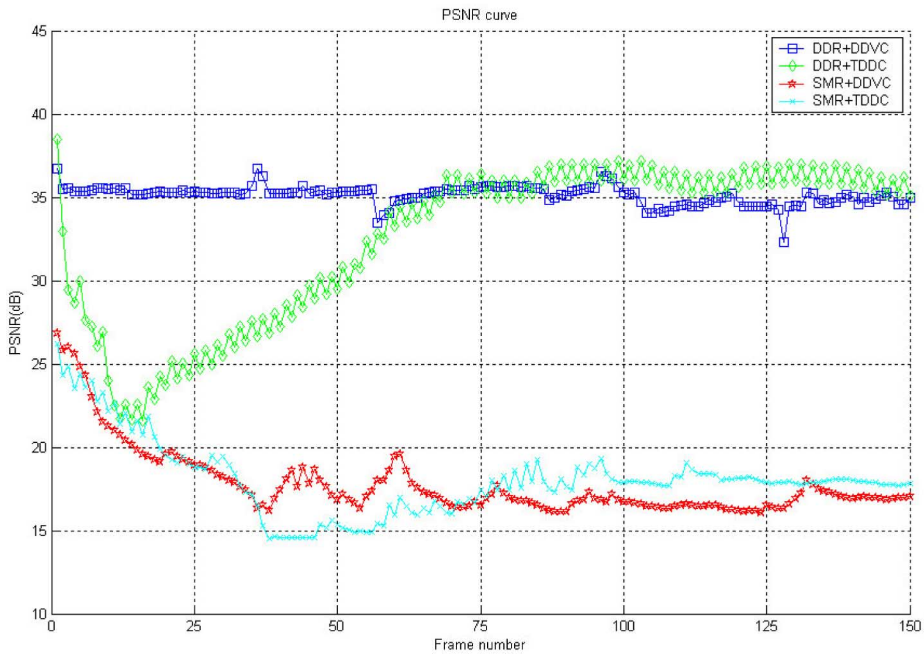

Fig. 20. ***Objective quality comparison of different encoders using different routing protocols: "Coastguard."***

major concern is the suitability of the medium access layer for real-time traffic where interferences from neighboring relay nodes can impact the multihop link performance. Thus, in this paper, we have considered differing multichannel approaches to improve the overall performance of the multihop communication for CSMA/CA networks. In the first approach, which is mainly concerned with a single-path communication network, we have developed a multichannel link partitioning scheme that is capable of effectively controlling the amount of intrapath interference. Based on the AODV routing protocol we then presented a systematic channel allocation to each active node along a multihop path. It was shown that, by using only a few nonoverlapping frequency bands, we can effectively eliminate interferences from further away nodes, thus improving the link throughput performance.

We have also developed a multichannel technique for multiple-path diversity routing. The DSR routing protocol has been used to implement this routing scheme. We have shown that this protocol can indeed reduce the probability of losing both routes simultaneously, which is a crucial factor for reliable transmission of video via two descriptions. Using a dual-description video-coding scheme, we have demonstrated that by eliminating the interference between multiple routes (interpath interference), we can considerably improve the quality of the received video signal. ■

Acknowledgment

The author wishes to thank Dr. B. Hu and Dr. S. Gao for their assistance in this work.

REFERENCES

[1] International Standard for Information Technology—Local and Metropolitan Area Networks-Specific Requirements—Part 11: Wireless LAN MAC and PHY Specifications, IEEE 802.11 WG, 1999.

[2] H. Gharavi, "Control based mobile ad-hoc networks for video communications," *IEEE Trans. Consum. Electron.*, vol. 52, pp. 383–391, May 2006.

[3] B. Hu and H. Gharavi, "DSR-based directional routing protocol for ad hoc networks," in *Proc. IEEE GLOBCOM 2007*, Washington, DC, Nov. 26–30, 2007.

[4] B. Yan and H. Gharavi, "Power control in multihop CSMA," in *Proc. IEEE Int. Symp. World of Wireless, Mobile and Multimedia Networks (WoWMoM06)*, Buffalo, NY, Jun. 2006, pp. 432–434.

[5] S. Corson and J. Macker, "Mobile ad hoc networking (MANET): Routing protocol performance issues and evaluation considerations," in *RFC 2501*, Jan. 1999.

[6] X. Hong, K. Xu, and M. Gerla, "Scalable ad hoc routing in large, dense wireless networks using clustering and landmarks," *IEEE Network*, vol. 16, pp. 11–21, Jul./Aug. 2002.

[7] C. E. Perkins, E. M. Royer, and S. Das, "Ad hoc on demand distance vector (AODV) routing," in *IETF Internet draft*, 2002, draft-ietf-manetaodv-10.txt.

[8] D. B. Johnson, D. A. Maltz, Y.-C. Hu, and J. G. Jetcheva, *The dynamic source routing protocol for mobile ad hoc networks (DSR)*, draft -ietf-manet-dsr-07.txt, Feb. 21, 2002.

[9] S. R. Das, R. Castaneda, and J. Yan, "Simulation based performance evaluation of mobile, ad hoc network routing protocols," *ACM/Baltzer Mobile Netw. Applicat. (MONET) J.*, pp. 179–189, Jul. 2000.

[10] C. E. Perkins *et al.*, "Performance comparison of two on-demand routing protocols for ad hoc networks," *IEEE Pers. Commun.*, pp. 16–28, Feb. 2001.

[11] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, "A performance comparison of multihop wireless ad hoc network routing protocols," in *Proc. ACM/IEEE MOBICOM'98*, Dallas, TX, Oct. 1998, pp. 85–97.

[12] S. R. Das, C. E. Perkins, and E. M. Royer, "Performance comparison of two on-demand routing protocols for ad hoc networks," in *Proc. IEEE INFOCOM 2000*, Tel Aviv, Israel, Mar. 2000, pp. 3–12.

[13] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.-L. Sheu, "A new multi-channel MAC protocol with on-demand channel assignment for multi-hop mobile ad hoc networks," in *Proc. Int. Symp. Parallel Architectures, Algorithms Netw. (I-SPAN 2000)*, Dec. 7–9, 2000, pp. 232–237.

[14] A. Nasipuri and S. R. Das, "Multichannel CSMA with signal power-based channel selection for multihop wireless networks," in *Proc. IEEE Veh. Technol. Conf. (IEEE VTS Fall VTC2000)*, Boston, MA, Sep. 24–28, 2000, pp. 211–281.

[15] A. Nasipuri and S. R. Das, "A multichannel CSMA MAC protocol for mobile multihop networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC'99)*, New Orleans, LA, Sep. 1999.

[16] J. So and N. H. Vaidya, *A multi-channel mac protocol for ad hoc wireless networks*, Dept. of Comp. Science, Univ. of Illinois at Urbana-Champaign, Tech. Rep., 2003. [Online]. Available: http://citeseer.ist.psu.edu/so03multichannel.html

[17] N. Choi, Y. Seok, and Y. Choi, "Multi-channel MAC protocol for mobile ad hoc networks," in *Proc. 58th IEEE Veh. Technol. Conf. (VTC2003)*, 2003.

[18] H. Zhai, J. Wang, Y. Fang, and D. Wu, "A dual-channel MAC protocol for mobile ad hoc networks," in *Proc. IEEE Global Telecommun. Conf. Workshop (GLOBECOM 2004)*, 2004, pp. 27–32.

[19] S.-L. Wu, Y.-C. Tseng, C.-Y. Lin, Lin, and J.-P. Sheu, "A multi-channel MAC protocol with power control for multi-hop mobile ad hoc networks," *Comput. J.*, vol. 45, no. 1, pp. 101–110, 2002.

[20] Y. Zhao, Y. Xiang, L. Xu, and M. Shi, "A multi-channel medium access control protocol for multicast in mobile ad-hoc network," in *Proc. 14th IEEE Personal, Indoor Mobile Radio Commun. (PIMRC 2003)*, Sep. 7–10, 2003, vol. 2, pp. 1639–1643.

[21] J. Li, Z. J. Haas, M. Sheng, and C. Y. Chen, "Performance evaluation of modified IEEE 802.11 MAC for multi-channel multi-hop ad hoc network," in *Proc. 17th Int. Conf. Adv. Inf. Netw. Applicat. 2003 (AINA 2003)*, Mar. 27–29, 2003, pp. 312–317.

[22] W.-C. Hung, K. L. E. Law, and A. Leon-Garcia, "A dynamic multi-channel MAC for ad-hoc LAN," in *Proc. 21st Biennial Symp. Commun.*, Kingston, Canada, Jun. 2002, pp. 31–35.

[23] P. Kyasanur and N. H. Vaidya, "Capacity of multi-channel wireless networks: Impact of number of channels and interfaces," in *Proc. 11th Annu. Int. Conf. Mobile Comput. Network.*, 2005, pp. 43–57.

[24] C. Xu, K. Liu, Y. Yuan, and G. Liu, "A novel multi-channel based framework for wireless IEEE 802.11 ad hoc networks," in *Proc. IEEE Int. Conf. Wireless Commun., Netw. Mobile Comput.*, 2005, Sep. 23–26, 2005, vol. 2, pp. 812–815.

[25] U. Lee, S. F. Midkiff, and J. S. Park, "A proactive routing protocol for multi-channel wireless ad-hoc networks (DSDV-MC)," in *Proc. Int. Conf. Inf. Technol. Coding Comput. (ITCC 2005)*, 2005, pp. 710–715.

[26] B. Yan and H. Gharavi, "Multi-path multi-channel routing protocol," in *Proc. 5th IEEE Int. Symp. Netw. Comput. Applicat. (NCA 2006)*, 2006, pp. 27–31.

[27] Tsirigos and Z. J. Haas, "Multipath routing in the presence of frequent topological changes," *IEEE Commun. Mag.*, vol. 39, pp. 132–138, Nov. 2001.

[28] S. Motegi and H. Horiuchi, "AODV-based multipath routing protocol for mobile ad hoc networks," *IEICE Trans. Commun.*, vol. E87-B, no. 9, pp. 2477–2483, Sep. 2004.

[29] S. K. Das, A. Mukherjee, S. Bandyopadhyay, K. Paul, and D. Saha, "Improving quality-of-service in ad hoc wireless networks with adaptive multi-path routing," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM '00)*, Nov. 27–Dec. 1, 2000, vol. 1, pp. 261–265.

[30] M. S. Jian and C. Lin, "Improved rank-based multi-path routing in mobile ad-hoc networks," in *Proc. IEEE Int. Conf. Adv. Commun. Technol. (ICACT 2005)*, Feb. 2005, vol. 2, pp. 1249–1254.

[31] I. S. Misra, D. Poddar, P. Nandi, U. Santra, and S. Panda, "Congestion controlled reliable multi path source routing in ad-hoc networks," in *Proc. IEEE Int. Conf. Personal Wireless Commun. (ICPWC 2005)*, 2005, pp. 72–76.

[32] Y. Z. Liu and W. K. G. Seah, "A priority-based multi-path routing protocol for sensor networks," in *Proc. IEEE Int. Symp. Personal, Indoor Mobile Radio Commun. (PIMRC 2004)*, Sep. 5–8, 2004, vol. 1, pp. 216–220.

[33] Nasipuri and S. R. Das, "On-demand multipath routing for mobile ad hoc networks," in *Proc. IEEE Conf. Comput. Commun. Netw.*, Oct. 11–13, 1999, pp. 64–70.

[34] S. J. Lee and M. Gerla, "AODV-BR: Backup routing in ad hoc networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC 2000)*, Sep. 23–28, 2000, vol. 3, pp. 1311–1316.

[35] H.-Y. An, L. Zhonq, X.-C. Lu, and W. Peng, "A cluster-based multipath dynamic source routing in MANET," in *Proc. IEEE Int. Conf. Wireless Mobile Comput., Netw. Commun. (WiMob'2005)*, 2005, pp. 369–376.

[36] S. J. Lee and M. Gerla, "Split multipath routing with maximally disjoint paths in Ad hoc networks," in *Proc. IEEE Int. Conf. Commun.*, 2001, vol. 10, pp. 3201–3205.

[37] P. P. Peter and S. Perreau, "Performance analysis of reactive shortest path and multi-path routing mechanism with load balance," in *Proc. IEEE INFOCOM*, 2003, vol. 1, pp. 251–259.

[38] S. Singh, M. Woo, and C. S. Raghavendra, "Power-aware routing in mobile ad hoc networks," in *Proc. ACM MobiCom'98*, Dallas, TX, 1998, pp. 181–190.

[39] H. Gharavi and K. Ban, "Multihop sensor network design for wideband communications," *Proc. IEEE*, vol. 91, pp. 1221–1234, Aug. 2003.

[40] L. Ozarow, "On a source coding problem with two channels and three receivers," *Bell Syst. Tech. J.*, vol. 59, pp. 1909–1921, Dec. 1980.

[41] V. A. Vaishampayan, "Design of multiple description scalar quantizer," *IEEE Trans. Inf. Theory*, vol. 39, pp. 821–834, May 1993.

[42] A. Ingle and V. A. Vaishampayan, "DPCM system design for diversity systems with applications to packetized speech," *IEEE Trans. Speech Audio Process.*, vol. 3, pp. 48–57, Jan. 1995.

[43] H. Jafarkhani and V. Tarokh, "Multiple description trellis coded quantization," *IEEE Trans. Commun.*, vol. 47, pp. 799–803, Jun. 1999.

[44] Y. Wang, M. Orchard, and A. R. Reibman, "Optimal pairwise correlating transforms for multiple description coding," in *Proc. IEEE Int. Conf. Image Process.*, Chicago, IL, Oct. 1998.

[45] Y. Wang, M. Orchard, V. Vaishampayan, and A. R. Reibman, "Multiple description coding using pairwise correlating transforms," *IEEE Trans. Image Process.*, vol. 10, pp. 351–366, Mar. 2001.

[46] V. K. Goyal, J. Kovacevic, R. Arean, and M. Vetterli, "Multiple description transform coding of images," in *Proc. IEEE Int. Conf. Image Process.*, Chicago, IL, Oct. 1998.

[47] M. Srinivasan and R. Chellappa, "Multiple description subband coding," in *Proc. IEEE Int. Conf. Image Process.*, Chicago, IL, Oct. 1998.

[48] Y. Wang, A. Reibman, and S. Lin, "Multiple description coding for video delivery," *Proc. IEEE*, vol. 93, pp. 57–70, Jan. 2005.

[49] A. Reibman, H. Jafarkhani, Y. Wang, M. Orchard, and R. Puri, "Multiple description coding for video using motion compensated temporal prediction," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 12, pp. 193–204, Mar. 2002.

[50] Y. Wang and C. Wu, "Low complexity multiple description coding method for wireless video," in *Proc. AINA*, Mar. 2005, vol. 2, pp. 95–98.

[51] S. Gao and H. Gharavi, "Multiple description video coding over multiple path routing networks," in *Proc. Int. Conf. Digital Telecommun.*, Cap Esterel, France, Aug. 2006.

[52] J.-W. Suh and Y. S. Ho, "Error concealment based on directional interpolation," *IEEE Trans. Consum. Electron.*, vol. 43, pp. 295–302, Aug. 1997.

[53] C. Bettstetter, G. Resta, and P. Santi, "The node distribution of the random waypoint mobility model for wireless ad hoc networks," *IEEE Trans. Mobile Comput.*, pp. 257–269, Jul. 2003.

ABOUT THE AUTHOR

Hamid Gharavi (Fellow, IEEE) received the Ph.D. degree from Loughborough University, Loughborough, U.K., in 1980.

He joined AT&T Bell Laboratories, Holmdel, NJ, in 1982. He was transferred to Bell Communications Research (Bellcore) after the AT&T-Bell divestiture, where he became a Consultant on video technology and a Distinguished Member of Research Staff. In 1993, he joined Loughborough University as a Professor and Chair of Communication Engineering. Since September 1998, he has been with the National Institute of Standards and Technology, U.S. Department of Commerce, Gaithersburg, MD. He was a core member of the Study Group XV (Specialist Group on Coding for Visual Telephony) of the International Communications Standardization Body CCITT (ITU-T). He was selected as one of the six university academics to be appointed to the U.K. Government's Technology Foresight Panel in Communications to consider the future through 2015 and make recommendations for allocation of key research funds. His research interests include video/image transmission, wireless multimedia, mobile communications and third-generation wireless systems, and mobile ad hoc networks. He has received eight U.S. patents related to these topics.

Dr. Gharavi has been a Guest Editor for a number of Special Issues. He is Deputy Editor-in-Chief of the IEEE Transactions on Circuits and Systems for Video Technology. Since January 2003, he has been a member of the Editorial Board of the Proceedings of the IEEE. He received the Charles Babbage Premium Award from the Institute of Electronics and Radio Engineering in 1986 and the IEEE CAS Society Darlington Best Paper Award in 1989. He is a Distinguished Lecturer of the IEEE Communication Society.