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Performance Evaluation of Directional Adaptive Range Control in Mobile Ad Hoc Networks

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Abstract. This paper presents DARC (Directional Adaptive Range Control), a range control mechanism using directional antennas to be implemented across multiple layers. DARC uses directional reception for range control rather than directional transmission in order to achieve both range extension and high spatial reuse. It adaptively controls the communication range by estimating dynamically changing local network density based on the transmission activities around each network node. The experimental results using simulation with detailed physical layer, IEEE 802.11 DCF MAC, and AODV protocol models have shown the successful adaptation of communication range with DARC for varied network densities and traffic loads. DARC improves the packet delivery ratio by a factor of 9 at the maximum for sparse networks while it maintains the increased network capacity for dense networks. Further, as each node adaptively changes the communication range, the network delivers up to 20% more packets with DARC compared to any fixed range configurations.

Keywords: mobile ad hoc networks, directional antenna systems, cross-layer interactions

1. Introduction

Directional antennas that can beamform or direct radiated power in a certain direction within microseconds have great potentials in improving the performance of wireless communication systems. The benefits of such directional antennas have already been demonstrated by their wide deployment at base stations in existing cellular networks, and this technology is expected to play an important role at mobile stations in future generation wireless communication systems. Small, lightweight and low-cost directional antennas [1,2,15,25] that meet physical restrictions of mobile stations are currently being developed with intense efforts.

While the antenna hardware will soon be ready for the deployment at mobile stations, existing higher layer protocols may not be able to fully exploit the potentials of directional communications. In particular, recent studies on the use of directional antennas in mobile ad hoc networks, or MANETs, have shown significant increase in network capacity. However, effective extension of communication range, another benefit of directional antennas demonstrated in cellular networks, has not been shown successfully. This is partly because the increase in network capacity can be achieved by modifying the protocol stack only up to the MAC sub-layer, while the communication range extension requires changes up to the network layer at which route selection is made based on the reachability to other network nodes. Directional antennas can provide considerable flexibility in setting up routes in the network, particularly for sparse networks where nodes may not otherwise be able to find a neighbor due to network partitions. However, controlling directional antennas in MANETs is more challenging than in cellular networks due to the lack of centralized control points like the base stations in cellular networks.

One important issue with communication range extension using directional antennas is possible increase of interference due to high EIRP (Effective Isotropic Radiated Power) in the transmission direction. High interference could increase contention among network nodes attempting to acquire the channel access, resulting in severely reduced network capacity. This is fatal for dense networks where many links share the same space; therefore, communication range extension should be performed adaptively to the network density and be used primarily for sparse networks with partitions.

However, identifying the network density itself is also challenging in MANETs. Unlike cellular networks where communication links are set up only between base stations and mobiles, traffic flows among network nodes can change dynamically subject to node mobility and routing protocol behaviors. Network nodes not participating in routing any traffic should not be counted when computing the effective network density. This results in instantaneous density changes even in networks with no mobility.

This paper presents Directional Adaptive Range Control (DARC), an adaptive range control mechanism using directional antennas. DARC adaptively controls the range by estimating dynamically changing local network density based on the transmission activities around each network node. It controls the communication range by directional reception rather than directional transmission such that the presence of long range links do not limit the network capacity.

DARC has been evaluated using detailed simulation with varied network densities and traffic loads, and has shown its benefits in terms of increased packet delivery and reduced end-to-end communication latency. The simulation results show that DARC improves the packet delivery ratio by as much as 9 times for sparse networks while it maintains the network capacity increased by directional antennas for dense networks.

Further, as each node adaptively changes the communication range, the network delivers up to 20% more packets with DARC compared to any fixed range configurations

The paper is organized as follows. The next section describes the related work, and Section 3 presents the DARC mechanisms in detail. Section 4 shows the simulation results with analysis of the DARC performance. Section 5 concludes this paper.

2. Related work

The use of directional antennas in MANETs has been proposed more than a decade ago [1,27], but extensive studies have been made [3,4,6,9,13,18,22–24] only recently as their deployment at mobile stations becomes realistic. Except for [6] and [18], the use of directional antennas is focused on the increase in network capacity by improving the spatial reuse, and communication range of each network node is kept the same for omnidirectional and directional communications.

Ramanathan [18] examined various configurations of network nodes with directional antennas. One of the configurations attempted the communication range extension by keeping the transmission power for directional transmission, but it did not improve the network performance due to reduced network capacity. The performance gain was reported only when the transmission power was reduced.

Choudhury et al. [6] proposed MMAC, a new MAC protocol that exploits communication range extension by forwarding RTS over multiple hops. The study uses both directional transmission and reception with no transmission power adjustment. Although the proposed protocol requires extensive channel and topological information for its implementation, its simulation study shows significant benefits from long distance links that can be established only by using directional antennas. Similar to the cases in [18], DMAC, its baseline directional MAC protocol (without multi-hop RTS) does not yield good performance due to high interference caused by no transmission power adjustment for directional transmission.

These two studies that attempted communication range extension are realized by using high EIRP for directional transmission, which can be harmful from the network capacity perspective. DARC takes a different approach as its main objective is achieving communication range control without limiting the overall network capacity.

There have also been several studies on MANET routing using directional antennas. Roy et al. [21] proposed a link state based routing protocol using directional antenna to improve spatial reuse and minimize the effects of route coupling. Nasipuri et al. [12] proposed techniques to reduce routing overhead by directional propagation of routing information and discussed the tradeoff between reduction in routing overhead and end to end delay of packets. Choudhury and Vaidya [5] evaluated the impact of varied transmission range on the performance of routing protocols. The study used a simple MAC protocol that realizes broadcasts using sequential directional transmissions and proposed three techniques to improve the performance of a routing protocol.

DARC is to be implemented across the physical, MAC and network layers although it needs minimal modifications at each layer. While the idea behind DARC is not bounded to any specific protocol at each layer, for simplicity of discussion, this paper describes the DARC implementation with the IEEE 802.11 [7,14] and AODV (Ad Hoc On-Demand Distance Vector Routing) [16] as used in many MANET studies. The following section describes the DARC mechanism at each of the three layers in detail.

3. Adaptive range control

3.1. Reception range control (PHY)

Figure 1 shows the power level of a signal transmitted at 15 dBm for omnidirectional communication (0 dBi antenna gain at both transmitter and receiver) as a function of distance with the two-ray path loss model [19]. It also includes two parameters used in the IEEE 802.11b card models. *RXT* (Reception Threshold) is a power level used at the receiver to assess whether the signal carries adequate power for reception without errors. *CST* (Carrier Sensing Threshold) is another threshold used by the receiver to assess the channel condition. If the sensed energy on the channel is above *CST*, the node defers the transmission of any pending signals.

Assuming no interference, the communication range is primarily determined by the given transmission power, antenna gains, *RXT* and path loss. While directional transmission and reception can provide the same gain (denoted as G_D [dBi] henceforth) for the link, they have a quite different impact on other communication links. Unless the transmission power is reduced accordingly, the directional transmission increases EIRP, which may cause a higher level of interference and limit the network capacity. On the other hand, the directional reception *does not* affect other communication links because the signal power levels sensed by other nodes do not change.

As one of the goals of DARC is controlling the communication range without limiting the network capacity, DARC uses *directional reception* for the range control. It reduces the transmission power by G_D for directional transmission to

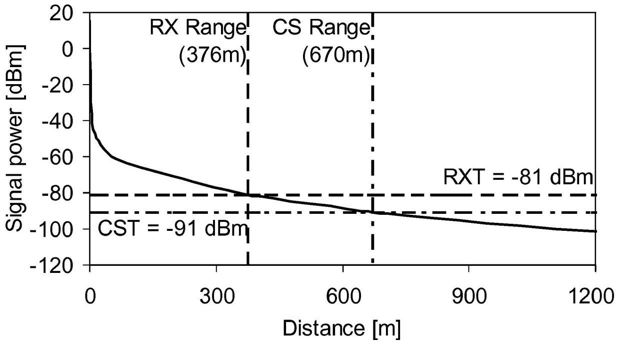

Figure 1. Signal power level PHY parameters.

keep the same EIRP level in the transmission direction, which can reduce the EIRP levels in other directions compared to the omnidirectional transmission. Although such directional transmission cannot extend the communication range, it can significantly increase the overall network capacity as shown in the past studies.

Even though directional reception does not limit the network capacity, it is sensitive to several parameters at the physical layer, and requires several adjustments. For instance, without any parameter adjustments for directional reception, the CS range becomes larger in the beamforming direction because the radio senses a high energy level due to amplification by the antenna gain. This could severely limit the network capacity similar to the directional transmission, as CSMA based MAC protocols do not transmit signals when the channel is busy. Therefore, DARC discounts the sensed energy by G_D before comparing it to *CST* in case of directional reception.

The directional reception can increase the signal power by G_D dB, but such gain is not limited to the desired signals, but also to interfering signals from the same direction. Therefore, DARC defines RXT_D, a reception threshold for directional reception whose value is slightly greater than *RXT* to account for fragility of directional reception. The relationships among *RXT*, RXT_D and G_D together with three signals S_A, S_B and S_C with different power levels are depicted in figure 2. In the figure, Signals S_A, S_B and S_C are amplified by directional reception and seen as S'_A, S'_B and S'_C respectively by the receiver. By raising the threshold for directional reception, the receiver attempts to receive S_B and S_C, but not $S_A$which is insufficient to reach RXT_D even with G_D.

If the power of directionally received packet was between RXT_D and $RXT + G_D$, the physical layer indicates the MAC protocol that the packet is received from a *faraway* node via an *extended* link as it could not be received in omnidirectional reception. For instance, S_B is from a faraway node while S_C is not, as the latter can be received even in omnidirectional reception. The transmitter of such signals is considered as a *nearby* node and the corresponded link is regarded as a *regular* link. This node and link classification is extensively used at the high layers to implement adaptive range control. DARC does not alter the protocol behaviors for communications through regular links, and only deals with extended links.

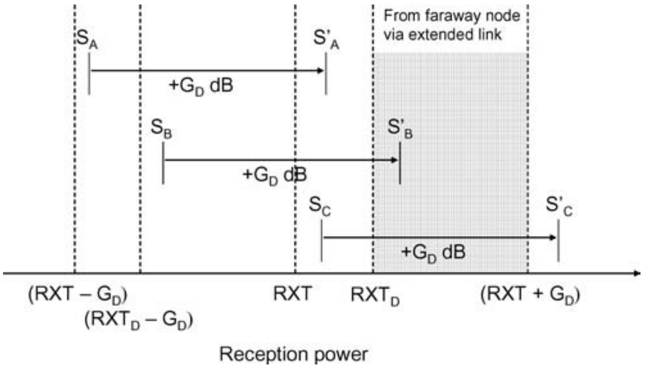

Figure 2. Reception thresholds in directional reception.

3.2. Link selection criteria (MAC)

3.2.1. DVCS

DARC uses Directional Virtual Carrier Sensing (DVCS) [24] as the baseline MAC extension to support directional antennas. DVCS is a set of simple enhancements for contention-based MAC protocols to support directional communications. It caches AOA (Angle of Arrival) information obtained by prior frame reception from neighboring nodes, and uses it for the subsequent directional transmissions. During the sequence of frame transmissions, each side fixes the antenna pattern for transmission and reception as well as carrier sensing to avoid communication distraction by interfering signals from other directions. It utilizes DNAV (Directional Network Allocation Vector), which is an extension to NAV used in the IEEE 802.11. DNAV reserves the channel only in certain directions and allows transmission in other directions to improve the spatial reuse.

In addition to AOA and reception time of the last signal, DARC caches the link classification reported by the physical layer. However, please note that each node updates the AOA and reception time even when overhearing a signal transmitted to other nodes, but not the link classification. While the physical layer maintains the same EIRP level in the transmission direction for both omnidirectional and directional transmissions, overheard signals may have been transmitted directionally in different directions. In that case, the node receives less signal power than signals transmitted omnidirectionally from the same transmitter. Therefore, the reception power of overheard signals is not used to classify the transmitter and the corresponding link, and the node does not update the cache table on the reception power.

3.2.2. Local network density

The selection of extended links in DARC is based on the local network density. As extensively studied in the past, the network density is one of the major factors to determine the overall network performance. By adaptively changing the communication range using directional antennas, each node can control the number of neighbors in order to yield better network performance.

DARC counts the number of nearby nodes in the cache table to estimate the local network density. As network nodes that have not transmitted a signal for a while are removed from the cache table, the node does not consider inactive nodes when estimating the local density. Therefore, the estimated network density naturally accounts for dynamically changing traffic flows and mobility in the network. For instance, even if the node is in densely populated area, it sees few nodes when surrounding nodes do not have data to transmit to the channel. Using extended links should be effective in such cases, as extended links do not limit the network capacity.

3.2.3. Robustness of extended links

As discussed in Section 3.1, links extended by directional reception are vulnerable to interference and collisions. In order to select robust and reliable links, DARC utilizes the number of nearby nodes in two different ways when assessing the quality of extended links. Suppose that Nodes X and Y can reach each other directly through an extended link. Let $n(\theta_1, \theta_2)$ denote the number of nearby nodes between two angles in the parentheses recognized by Node X. n_{all} and n_θ for Node Y are defined as follows:

$$n_{\text{all}} \equiv n(0, 360)$$

$$n_\theta \equiv n(\theta - D/2, \theta + D/2)$$

where θ is AOA from Node Y, and D is the angle of DNAV used in DVCS4 at Node X.

n_{all} is the total number of nearby nodes recognized by Node X and is correlated to the amount of interference that Node X may experience when receiving signals from other nodes. As shown in the literature [10,20], directional antennas could leak rather large amount of energy in directions other than the beamforming direction. Therefore, even if nearby nodes transmit signals in directions away from Node X, such transmissions can cause high interference at Node X. This would happen frequently with DVCS, as nearby nodes setting a DNAV for Node X can still transmit signals in other directions. Therefore, having many nearby nodes can cause high interference, or prevent Node X from responding to RTS transmitted by Node Y due to physical carrier sensing.

n_θ is the number of nearby nodes whose DNAVs include the AOA of Node Y, and may force Node X to set a DNAV in the direction of Node Y. Upon overhearing frames from those nearby nodes, Node X is unable to respond to Node Y even if it receives an RTS frame without errors from Node Y until all DNAVs are expired. Having no such nearby node can make the extended link more robust, as there is no contention with nearby nodes.

Please note that neither n_{all} nor n_θ includes the number of faraway nodes because faraway nodes contribute less interference than nearby nodes in general, and DNAVs are not set for overheard frames from faraway nodes. However, faraway nodes may still have large impacts on the robustness of extended links as weak signals from many faraway nodes can be accumulated to high interference. Better link robustness assessment by accounting for faraway nodes recognized by the physical layer is to be investigated in our future work.

In this study, DARC uses the following two conditions as the reception condition when assessing the robustness of extended links:

$$\text{Omnidirectional condition:} \quad n_{\text{all}} \leq M$$

$$\text{Directional condition:} \quad n_\theta = 0$$

where M is a constant determined by the capability of the underlying antenna system. Note that the use of the directional condition can be optional while the omnidirectional condition is mandatory, as the node would suffer from high interference when n_{all} is high even with no nearby node in the communication direction.

The MAC protocol checks these conditions every time it receives a frame from a faraway node not in the cache table, and passes the information up to the network layer. Once the network layer decides to communicate with the new faraway node, the MAC protocol updates the cache table with an entry for the new node.

3.3. Route selection (network)

In this study, AODV is used as the base routing protocol. Like many other routing protocols, AODV uses the hop count to the destination when selecting a route. This can create a tendency that it chooses routes that include many extended links to reduce the hop counts, but such routes may be vulnerable to interference and collisions. As the overhead of finding an alternative route is significant when the existing route breaks, the routing protocol should not use extended links unless they are reasonably robust and reliable.

In AODV, route requests (RREQs) are broadcast and flooded in the network when a data source has no route to the destination. The route is set up when route replies (RREPs) are relayed back from the destination to the source. It is important to note that in this route discovery process, the transmission direction of RREQs is equal to the direction of application data.

The DARC implementation in this paper uses these AODV control messages to assess the quality of routes. Each node rebroadcasts RREQ messages from a faraway node only when the corresponding extended link meets the reception condition. As a RREQ message must have been accepted at each node on the route in the route discovery process, all the extended links on the route are guaranteed to clear the reception condition in the direction of application data stream. Dropping RREQs through unreliable extended links eliminates the possibility for AODV to include unreliable extended links in the route.

Please note that this mechanism itself does not explicitly check the reception condition at intermediate nodes on the route in the reverse direction. With the IEEE 802.11 MAC protocol, the unicast communication involves both directions of frame reception, as ACK frames are always transmitted in the other direction of DATA frame transmission. As the surrounding environment of one side can be quite different from that of the other node for a single link, each extended link should be established after examining the reception conditions at both sides. Otherwise, it is possible for unicast packets to not go through the route even if the reception condition is excellent in the direction of application data stream.

As the RREPs are always transmitted through the route in the reverse direction in AODV, each node can check the reception condition for RREPs to ensure the quality of extended links in the reverse direction. Note, however, that the reception condition for the reverse path does not have to be as strict as the condition for RREQs, as the MAC control frames (CTS and ACK) to be transmitted in the reverse direction are very small compared to data frames. Section 4.3.4 examines cases with different levels of reception conditions for each direction of extended link.

When the reception condition for an extended link is different in each direction, AODV needs to be modified further, as it may use, or share parts of existing routes to send application data in the reverse direction even if the extended link satisfies the reception condition only directionally. The following summarizes the enhancements made to AODV to handle directional extended links (DELs) appropriately:

- Each RREQ message carries a flag to indicate if the message has been relayed through an extended link.
- When a node receives a RREQ message with the flag not set, it checks whether it received the message via an extended link. If so, it sets the flag before rebroadcasting the RREQ message.
- When a node receives a RREQ message with the flag, it creates the reverse path but indicates in its route table that the path from the source includes at least one extended link whose reception condition may be satisfactory only directionally.
- When a node receives a RREQ message whose destination is reachable only through the reverse path of an existing route that includes an extended link, the node rebroadcasts the RREQ message without using the reverse path. Also, unless a source has a route that is explicitly examined in the direction of the destination, it initiates the route discovery process.

With these modifications, AODV does not reuse routes with DELs unless the reception condition at each intermediate node is explicitly examined in the reverse direction.

4. Experimental results

As DARC uses the directional reception as well as the cache based network density for the communication range control, detailed simulation of interference and collisions is necessary to evaluate the DARC performance. In this study, DARC is evaluated using QualNet [17], which supports simulation of directional antenna communications with a rich set of higher layer protocols. The table below summarizes the set of parameters used to configure the physical layer and the MAC protocol in the study.

Table 1
Set of parameters used in the simulation study.

Antenna Parameters	
Antenna gain	15.5 [dBi]
Antenna beamwidth	45°
Other Physical Layer Parameters	
Channel frequency	2.4 [GHz]
Signal reception	BER based (DBPSK modulation)
Data rate	2 [Mbps]
Noise figure	7.0 [dB]
TX power (directional)	15.0 (0.0) [dBm]
RXT	−81.0 [dBm]
CST	−91.0 [dBm]
MAC Sub-Layer Parameters	
DNAV width	74°
Cache entry expiration time	2.0 [s]
Directional RTS trials	4
M(number of nearby nodes)	4

4.1. Antenna model

The directional antenna model used in this study is an electrically steerable beamforming antenna. Six isotropic antenna elements are placed to form a circle whose radius (and the space between adjacent elements) is 0.4 wavelength of the carrier frequency. In order to form a beam for a given direction, the antenna system combines inputs from all the antenna elements. Assuming the AOA of each signal is identical for all the elements, the antenna system can maximize the output by adjusting the phases of the 6 inputs to be the same, which results in the 15.5 dBi antenna gain and 45° beamwidth regardless of the given AOA. Therefore, it can electrically steer the beam with the constant antenna gain to any directions on the azimuth plane. While this antenna system has no ability to null out strong interfering signals, it is easier to understand and analyze its behaviors because of the constant gain, which also allows the physical layer to easily notify the MAC protocol of the normalized reception power.

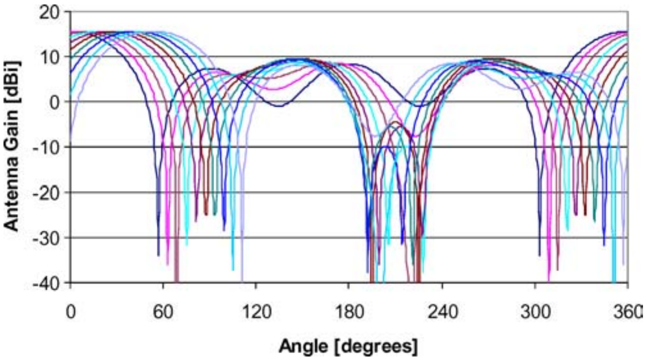

Figure 3. Antenna patterns for different directions.

As repeatedly pointed out in this paper, it is essential to use realistic radiation patterns that include not only the gain in the transmission direction but also gains in all other directions, as energy leaked in other directions creates significant interference on other ongoing communications. The radiation patterns for this antenna system have been created using MATLAB and shown in figure 3. The figure includes ten lines representing antenna patterns whose beamforming directions are ranging from 0 to 54 degrees at 6 degree intervals. As shown, while the antenna gain remains constant in the beamforming directions, the shapes of side lobes change as the beamforming direction is steered from 0 to 60 degrees due to the physical configuration of the antenna system. Moreover, the result shows that the gains for side lobes may become only 6 dB less than that for the main lobe, which would cause high interference in other directions. These patterns are fed into QualNet for the simulation of realistic interference in directional antenna communications.

4.2. Simulation scenario

Scenarios used in this study are configured as follows. A hundred nodes are randomly placed on TS by TS m flat terrain

Table 2
Average number of nodes within each range.

TS [m]	Number of nodes in the RX range	Number of nodes in the CS range
2000	11.10	35.25
3000	4.93	15.66
3500	3.62	11.51
4000	2.77	8.81
4500	2.19	6.96
5000	1.77	5.64
5500	1.46	4.66

where *TS* (Terrain Size) is varied to change the average network density (*TS* = 2000, 3000, 3500, 4000, 4500, 5000 and 5500 m). Forty CBR (Constant Bit Rate) sessions are set up between two randomly chosen nodes. Each CBR session generates 512 byte data packets at a rate of L (=2, 4, 6, 8, 10, 12 and 14) packets per second throughout the simulated duration of 180 seconds. *NL* (Network Load) is defined as the number of CBR sessions multiplied by L, and *TS* and *NL* are the primary parameters to configure various cases. Each node continuously moves on the terrain based on the random waypoint mobility model at the speed of 10 m/s with no pause.

Even when the communication range is extended from the original RX range to the CS range, the number of neighbors that each node can discover increases significantly. Table 2 shows the average number of nodes in each range for the given *TS*, excluding the terrain boundary effect. The average number of nodes is calculated as follows:

$$\bar{n} = \frac{N\pi r^2}{(TS)^2}$$

where N is the number of nodes in the network and r is the radius of the given range. As shown, while each node has enough number of neighbors (11.10) to configure the network at *TS* = 2000 m even without extending the range, it has too few neighbors on average (1.46) when *TS* is set to 5500 m, in which case network partitions are likely to happen. The range of *TS* is chosen to test DARC, as extending the range for *TS* = 2000 m with high network loads should limit the network capacity while it is crucial to extend the range for *TS* = 5500 m to solve network partitions.

For the given network scenario, the following node configurations are examined:

- OA-RR (Omnidirectional Antenna with Regular Range)
  In OA-RR, each node is equipped with an omni-directional antenna whose antenna gain is 0 dBi. This is included as a reference point of network performance in pure omnidirectional communication without range extension.
- OA-WR (Omnidirectional Antenna with Wide Range)
  In OA-WR, each node also uses the omnidirectional antenna, but *RXT* is set to −91 dBm equal to *CST*. This setting demonstrates the effects of communication range extension *without* directional antennas.
- DA-RR (Directional Antenna with Regular Range)
  This configuration is identical to OA-RR, except that each node is equipped with the directional antenna. This is considered to be the baseline configuration with directional antennas.
- DA-WR (Directional Antenna with Wide Range)
  This configuration corresponds to OA-WR with the directional antenna. RXT_D is set to −76 dBm equal to $CST + G_D$, which makes the communication range of this configuration equal to that of OA-WR.
- DARC
  DARC is the configuration to be evaluated in this study. Unless otherwise noted, DARC utilizes the directional reception condition only for the RREQs, which yielded the best performance among several variations as shown in Section 4.3.4.

To obtain reliable simulation results, ten cases per combination of *TS* and *NL* are created with different random number seeds. Together with 3 additional variations of DARC node configurations examined later, this entire simulation study consists of nearly 4,000[1] simulation runs.

4.3. Simulation results

4.3.1. Packet delivery with varied density

Four charts in figure 4 show the aggregated packet delivery ratios (PDRs) for all CBR sessions at fixed network loads (*NL* = 80, 160, 240 and 320 pps), which indicate how each node configuration performs against varied network densities. At *NL* = 80 pps, all the configurations perform very well for dense network cases, as neither network capacity nor partition is an issue for such cases. As *TS* increases, OA-RR and DA-RR fail to yield good PDRs because network nodes with the original RX range find few neighbors in these configurations. It is interesting to note that OA-WR, which does not use directional antennas, performs reasonably well, as it does not suffer from contention at this network load. DA-WR performs the best among all the configurations while DA-DARC closely follows DA-WR. At *TS* = 5500 m, both DA-WR (PDR: 0.75) and DARC (PDR: 0.73) delivers almost 9 times more packets than DA-RR (PDR: 0.08) by preventing network partitions.

When *NL* is doubled (*NL* = 160 pps) as shown in the second chart, OA-RR and OA-WR that use only omnidirectional antennas start to suffer from the limited network capacity for dense network cases. For these configurations, OA-WR performs worse than OA-RR for *TS* = 4000 m and less, while it still delivers more packets than OA-RR at *TS* = 5000 and 5500 m. This shows that the wider communication range used in OA-WR limits the network capacity more than the regular range used in OA-RR due to higher density for the same network. Another wide range configuration, DA-WR has not yet suffered from the limited network capacity unlike OA-WR at this network load, as the directional transmission with reduced transmission power increases the base network capacity significantly. The network performance with the three directional

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[1] Total number of simulation runs: 7 (TS's) × 7 (NL's) × 8 (node configurations) × 10 (random numbers) = 3,920.

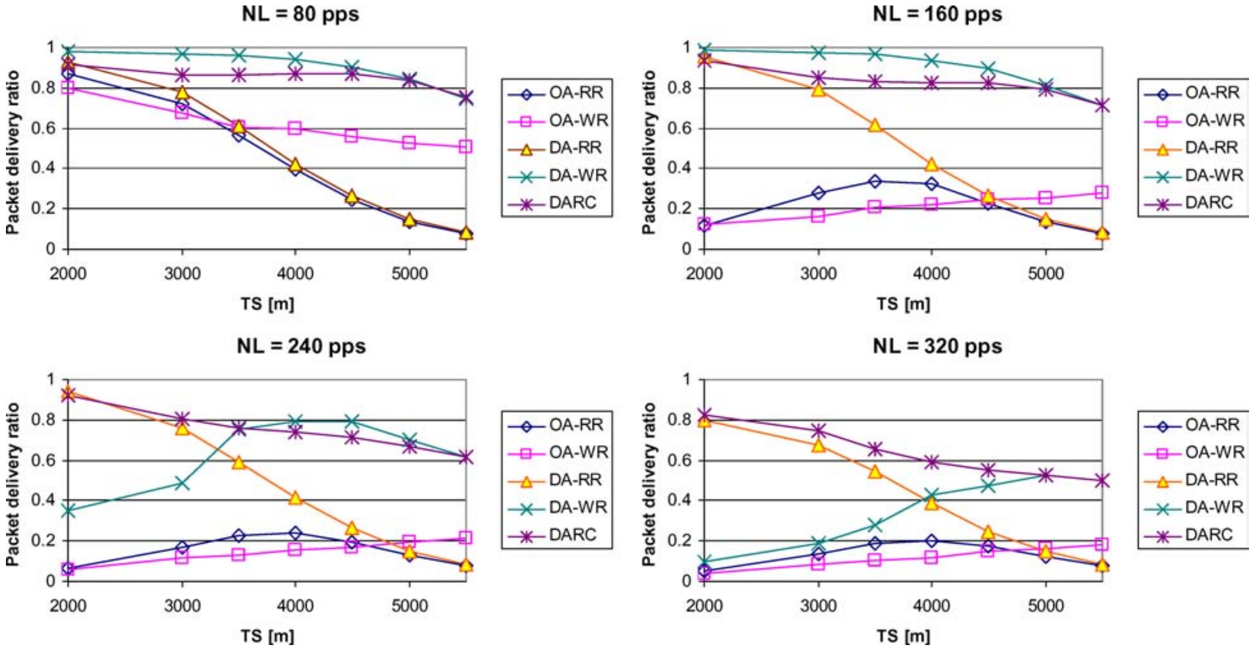

Figure 4. PDRs with varied terrain size.

antenna configurations is almost unchanged for *NL* = 80 and 160 pps.

At *NL* = 240 pps, however, the performance of DA-WR starts to degrade and becomes substantially worse than DA-RR and DARC for dense network cases. The cause of this performance degradation is the same as that of OA-WR at *NL* = 160 pps, showing the side effect of communication range extension. DARC successfully adapts its behavior to DA-RR to avoid limiting network capacity for dense network cases while still following the performance of DA-WR for sparse network cases.

The last chart for *NL* = 320 pps holds the same trends seen at *NL* = 240 pps, with DA-WR degrading its performance further and yielding only less than 0.1 PDR at *TS* = 2000 m. On the other hand, DARC does not degrade its performance much even at this network load for both dense and sparse networks, yielding 0.82 PDR at *TS* = 2000 m and 0.5 PDR at *TS* = 5500 m. As shown, it is the best performer for all network densities among these configurations, demonstrating its successful adaptive range control capability.

4.3.2. Packet delivery with varied traffic load

This subsection shows how DARC adapts its behavior against varying network loads. Four charts in figure 5 show the same set of experiments in the previous subsection, but from a different dimension by varying *NL* at fixed terrain sizes (*TS* = 2000, 3000, 4000 and 5000 m). At *TS* = 2000 and 3000 m, the performance trend of DARC is similar to that of DA-RR for all given network loads, while its performance becomes close to that of DA-WR at *TS* = 5000 m. At *TS* = 4000 m, DARC follows DA-WR for light network loads and starts to perform better than all other configurations by reducing the use of extended links as the network load increases. This demonstrates not only the successful adaptation of DARC against varying network loads, but also the fact that the appropriateness of using extended links changes even for the same network density depending on the given network load. This is important to point out as it indicates that local network density based on the number of active nodes nearby is a proper metric for the communication range extension, which changes with the network load. The conventional definition of network density used in Table 2 does not change with the network load, as it is purely a function of the number of nodes over the given area.

At *TS* = 2000 m, DARC delivers up to 20% more packets compared to DA-RR for high *NL* cases. This is unexpected but is an additional benefit of AODV modifications for DELs, which will be described in Section 4.3.5. For other terrain sizes, DARC outperforms the corresponding fixed range configurations (DA-RR and DA-WR) for most cases. As it does not change the regular link handling, its consistently better performance over that of DA-RR at *TS* = 3000 m indicates that even networks at relatively high density on average include locally sparse subnetworks where extended links can still be useful to improve the overall network performance.

Please also note, however, that DARC fails to follow DA-WR for light network load cases even though DA-WR performs better than DA-RR, particularly for *TS* = 3000 and 4000 m in figure 5. This is due to the fact that the current link selection mechanism used in DARC considers the number of active neighbors, but not how much traffic that each active neighbor carries. For instance, it may be still appropriate for a node to establish extended links even if it discovers more than *M* active nodes near by, each of which needs to transmit only little data to the channel. In such cases, the node does not establish extended links in the current DARC mechanism although the reception (contention) conditions for the node are

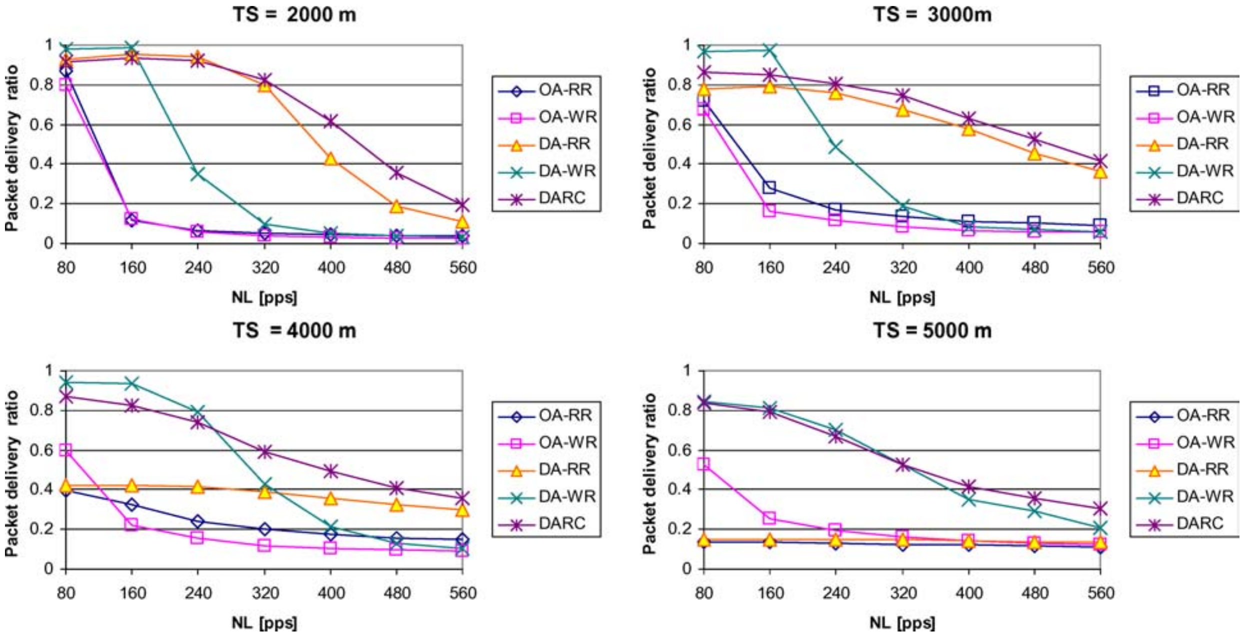

Figure 5. PDRs with varied network load.

not much different from fewer active nodes nearby. The current reception condition to select extended links needs to be modified to account for the traffic load, which should improve the DARC performance under such network scenarios.

4.3.3. Hop count and end-to-end delay

Figure 6 shows the average hop count as well as the average end-to-end delay with each node configuration at *TS* = 3000 m. Unlike PDR, which is based on the total number of packets given to the network, these data are based only on packets actually delivered to the destinations; therefore, each line can be compared with another only when their PDRs are close to each other. As shown in figure 6, the PDRs with OA-RR and OA-WR are close together while the former is slightly but consistently higher than the latter. Also, DA-RR and DARC have the same trend with the former slightly lower than the latter. For the better visibility, the lines for DA-WR are omitted in figure 6 as there is no node configuration with comparable PDRs. As shown in the first chart, both OA-WR and DARC are reducing the average number of hops for all network loads when compared with OA-RR and DA-RR respectively. In particular, OA-WR reduces the average hop count by up to 2, more than 30% reduction.

However, in the second chart, the average end-to-end delay with OA-WR is 2 to 2.5 times longer than that with OA-RR. This is somewhat controversial given that OA-WR reduces the hop counts by 30%, which should shorten the end-to-end delay by reducing the store-and-forward overhead incurred at intermediate nodes. However, when a route includes an unreliable extended link, the transmission of each packet may struggle on that link. In the IEEE 802.11 DCF MAC, if a sender fails to receive a CTS or ACK frame back from the receiver for its RTS or data frame transmission, it needs to retransmit the same frame after exponential back-off. As this retransmission overhead is significantly longer than the store-and-forward overhead, reducing the hop count by including unreliable extended links can substantially increase the average end-to-end delay.

DARC, on the other hand, successfully reduces both hop count and end-to-end delay, as it avoids the use of unreliable

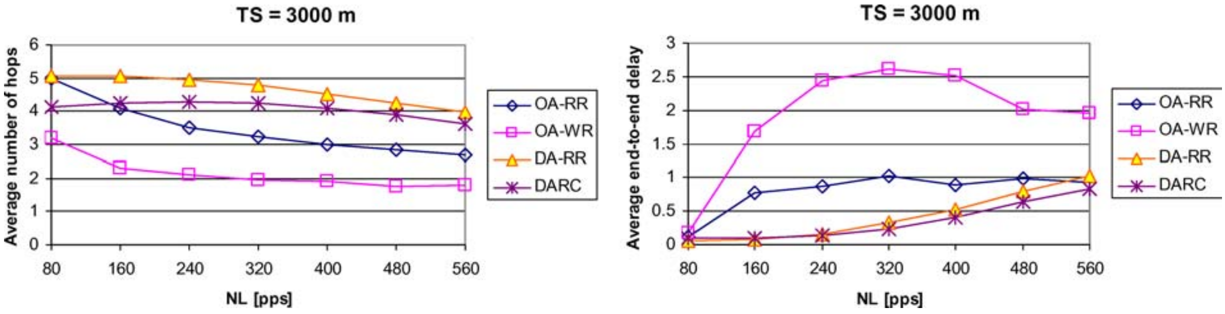

Figure 6. Average hop count and end-to-end delay.

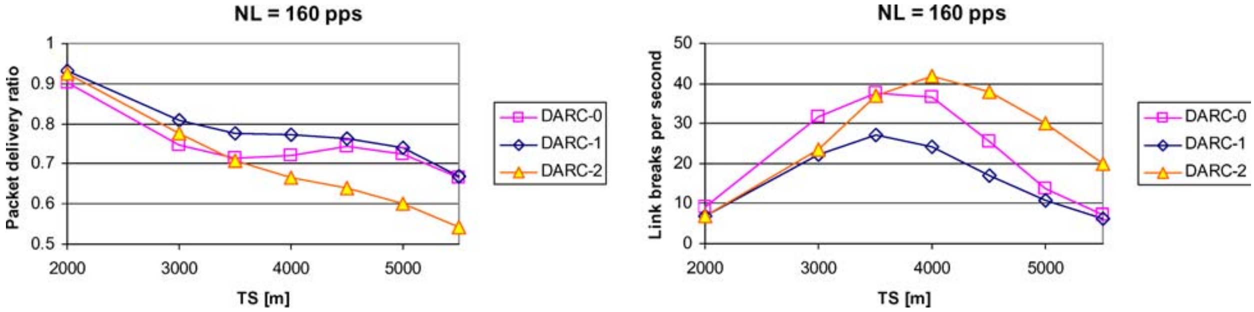

Figure 7. PDRs and link breakage frequencies with different reception conditions.

extended links when setting up routes. As long as extended links used on the routes are robust and reliable, they can reduce the number of hops to destinations without increasing the average end-to-end delay.

4.3.4. Link selection conditions

This subsection examines the effects of reception conditions used at each side of extended link on the overall network performance. Figure 7 shows the PDRs and the number of link breaks per second at $NL = 160$ pps with different reception conditions for DARC to assess the quality of extended links. As described in Section 3.3, while the omnidirectional reception condition is necessary for the quality assessment, the directional reception condition can be optional. Three lines in the figure indicate the following DARC variations:

- DARC-0: it does not use the directional condition for either direction of the link.
- DARC-1: it uses the directional condition for the direction of RREQs (application data) but not for the reverse direction.
- DARC-2: it uses the directional condition for both directions of the link.

Among these variations, the DARC performance shown so far is DARC-1. DARC-0 and DARC-2 use the same reception condition for both directions of each extended link, and are more aggressive or conservative than DARC-1 in including extended links in the routes.

As shown in the first chart, DARC-1 achieves the best performance among these three for all terrain sizes. DARC-0 uses the loosest condition among them, as it does not check the directional reception condition in either direction of the link. Therefore, its performance is the worst for dense network cases as it may use less reliable links that do not clear the directional reception condition. On the other hand, DARC-2 is too conservative to use extended links, having the worst performance for sparse networks. Although each link needs to accept frames from both sides for unicast communications in the IEEE 802.11, control frames to be transmitted in the other direction of data are small. Further, the backoff procedure in the IEEE 802.11 is not performed in the reverse direction, which makes the directional reception condition that examines how likely the direction is blocked by DNAVs less important. Therefore, extended links are reasonably robust even if the reverse direction does not meet the directional condition. When such directionally robust links are not used, more RREP messages are simply dropped at intermediate nodes, which may force the data source to time out and broadcast RREQ messages again until it finds a route. This significantly increases the route discovery overhead of AODV.

The second chart in figure 7 shows the effects of many RREP message drops with DARC-2. Please note that a RREP message dropped by the DARC link selection is counted as one link break in the statistics. As shown, DARC-2 has the highest number of link breaks among them for sparse network cases despite of its strict reception conditions. DARC-1 has the least number of link breaks among them for all terrain sizes, indicating that the directional reception condition in the direction of application data helps choose robust extended links, while not using the directional condition in the reverse direction does not increase the link breaks. Rather, it helps AODV acquire high quality routes without increasing the route discovery time.

4.3.5. Effects of AODV modifications for DELs

As shown in Section 4.3.2, DARC outperforms its base configuration (DA-RR) by up to 20% in PDR at $TS = 2000$ m for $NL = 400$ pps and higher. This performance improvement cannot be explained simply as the benefit of using reliable extended links, because DARC becomes conservative in using extended links as the traffic load increases, particularly for dense networks. Figure 8 shows the PDRs with DARC with and without the AODV modification for DELs described in Section 3.3 at $TS = 2000$ and 4000 m. Two additional lines for DA-RR and DA-WR are shown in the figure for reference.

As shown, the DARC performance without the AODV modification for DELs is almost identical to that of DA-RR for high network load cases at $TS = 2000$ m. The intended effects of the AODV modification for DELs are shown at $TS =$ 4000 m where it uniformly improves the DARC performance by avoiding the reuse of DELs in the reverse direction unless their reverse direction is explicitly examined.

Various statistics collected in the simulation indicate that the AODV modification for DELs creates a tendency of increasing the number of unshared routes in the network, as

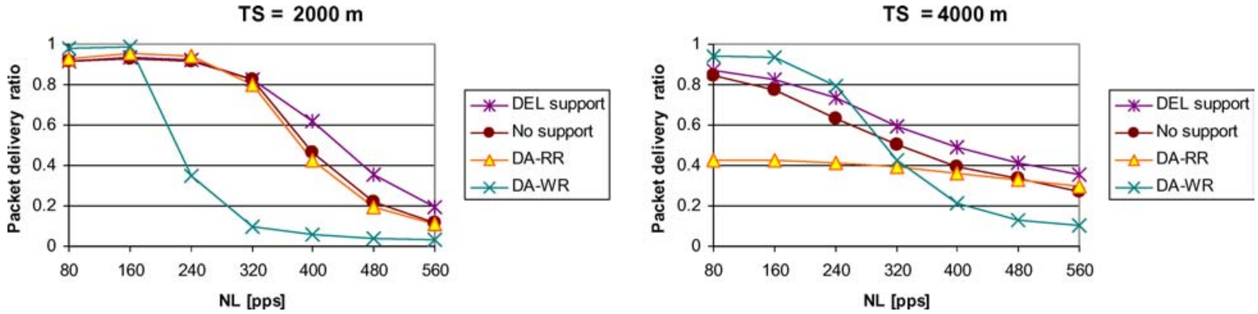

Figure 8. PDRs with and without the AODV modification for the DEL support.

routes including extended links are not reused unless their quality is explicitly checked in the reverse direction. This diversifies the routes set up for different application sessions, reducing the number of heavily loaded links in the network. This results in increased aggregate network throughput when the network is highly loaded, as heavy traffic creates many fully utilized links in the network. While further discussion on the effects of route diversification is to be made, it is beyond the scope of this paper and is to be investigated as our future work.

5. Conclusions

This paper has presented DARC (Directional Adaptive Range Control), a communication range control mechanism using directional antennas to be implemented across multiple layers. DARC uses directional reception for range control rather than directional transmission such that extended communication links do not increase interference to other ongoing communications. It adaptively controls the communication range by estimating dynamically changing local network density based on the transmission activities around each network node.

The experimental results using simulation with detailed physical layer, IEEE 802.11 DCF MAC, and AODV protocol models have shown the successful adaptation of communication range with DARC for varied network densities and traffic loads. DARC improves the packet delivery ratio by a factor of 9 at the maximum for sparse networks while it maintains the increased network capacity for dense networks. Further, it delivers up to 20% more packets to destinations compared to any node configurations with a fixed communication range as the result of range adaptation.

Further investigation on the use of directional antennas in MANETs is to be made. In this study, DARC used the signal reception power and the number of active neighbors nearby for the link classification and selection. While it is shown as very effective, DARC performed slightly worse than the node configuration with a fixed wide communication range for low network load cases. This indicates that the current link selection is somewhat conservative when the network capacity is not an issue. Considering the local network load in addition to the local network density would further improve the performance of DARC, which is our future work.

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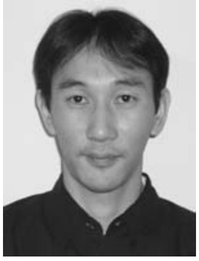

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