Adaptive Range Control Using Directional Antennas in Mobile Ad Hoc Networks

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ABSTRACT

This paper presents ARC (Adaptive Range Control), a communication range control mechanism using directional antennas to be implemented across multiple layers. ARC 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 ARC for varied network densities and traffic loads. ARC 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.

Categories and Subject Descriptors

D.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *Wireless Communication, Directional Antenna Systems.*

General Terms

Performance, Design, Experimentation, Verification.

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 spatial reuse 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.

However, while the antenna hardware itself 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 antennas. In particular, recent studies on the use of directional antennas in mobile ad hoc networks, or MANETs, have shown significant increase in network capacity by improving the spatial reuse, but effective extension of communication range has not been successfully demonstrated, which is another benefit of directional antennas in the cellular networks. This is partly because the increase in network capacity can be demonstrated by modifying the protocol stack only up to the MAC sub-layer, while the extension of communication range requires changes up to the network layer where route selection is made based on the reachability to other network nodes. The extension of communication range is critical for sparse networks where nodes may not be able to find a route to destinations due to network partitions. Directional antennas can potentially establish links between nodes far away from each other, preventing network partitions and providing considerable flexibility in setting up routes in the network. However, in MANETs where the network is configured autonomously without reliance on any underlying infrastructure, controlling directional antennas is more challenging than in cellular networks due to the lack of centralized control points.

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 for their data communications. Therefore, communication range extension should be based on the network density and be used primarily for sparse networks with partitions.

However, identifying the effective network density for communication range extension is also challenging in MANETs. Unlike cellular networks, 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 for networks without mobility.

This paper addresses these issues with Adaptive Range Control (ARC), a communication range control mechanism using

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directional antennas. ARC adaptively controls the communication 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 extended communication links do not increase interference to other ongoing communications.

ARC 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 ARC improves the packet delivery ratio by as much as 9 times for sparse networks while it maintains the increased network capacity for dense networks.

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

2. RELATED WORK

The use of directional antennas in MANETs has been proposed more than a decade ago [15][16], but extensive studies have been made [1][4][7][10][12][13] only recently as their deployment at mobile stations becomes realistic. Except for [1] and [10], 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 [10] 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, Yang et al. [1] 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 [10], 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. As the main objective of ARC is to control the communication range of each network node adaptively without limiting the overall network capacity, the approach to extend the communication range must be significantly different from the prior work as described in the following sections.

ARC uses the baseline MAC extension to support directional antennas by Takai, Martin et al. [13]. DVCS (Directional Virtual Carrier Sensing) presented in the study 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.

ARC is to be implemented across the physical, MAC and network layers although it needs minimal modifications at each layer. While the idea behind ARC is not bounded to any specific protocol at each layer, for simplicity of discussion, this paper describes the ARC implementation with the IEEE 802.11 [2] and AODV (Ad Hoc On-Demand Distance Vector Routing) [8] as used in many MANET studies. The following section describes the ARC 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 [11]. 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 decide whether or not to receive each signal on the channel. If the receiver is located more than 376m away from the transmitter where the reception power is below *RXT*, it does not try receiving the signal, which carries inadequate power to be received without errors. *CST* (Carrier Sensing Threshold) is another threshold used for physical carrier sensing. If the power from all signals (plus thermal noise) on the channel is above *CST*, the radio considers the channel to be busy and defers the transmission of any signals.

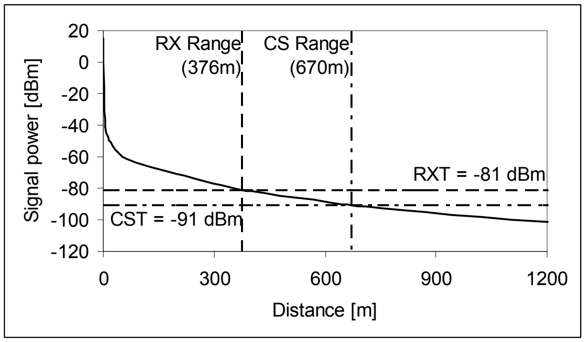


Figure 1: Signal power level PHY parameters

Assuming no interference, the communication range is primarily determined by the given transmission power, antenna gains, *RXT* and path loss. When a directional antenna is used at either side of the link, the maximum distance to set up a link is increased. Adding the antenna gain at the transmitter is equivalent to increasing the transmission power in the transmission direction, while adding the gain at the receiver corresponds to lowering *RXT* as the signal reception power is amplified.

Although directional transmission and reception provide the same gain for the corresponding 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 ARC is controlling the communication range without limiting the network capacity, ARC focuses on the use of directional reception for communication range extension. For the directional transmission, ARC reduces the transmission power by the antenna gain to keep the same EIRP level in the transmission direction, which can reduce the EIRP levels in other directions compared to the omnidirectional transmission. Although directional transmission at reduced power cannot extend the communication range, it can significantly increase the overall network capacity as shown in the past studies.

While directional reception does not limit the network capacity unlike directional transmission, it is sensitive to several physical layer parameters. If *CST* remains constant for the 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. However, 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, for directional reception, *CST* needs to be increased by the antenna gain, or set to the same value as *RXT* if the antenna gain is more than the difference between *CST* and *RXT*, which leads to the CS range being equal to the RX range. In omnidirectional communications, *CST* is typically set such that the CS range becomes two times the RX range [3] in order to avoid the hidden terminal problem [14]. As this cannot be held for the reason above, the range extension by directional reception is unable to rely on physical carrier sensing to avoid collisions. Therefore, packet exchanges via links extended by directional reception are more vulnerable to interference and collisions, and selection of such links must be done carefully to not degrade the overall network performance due to frequent link breaks.

As the physical layer does not have knowledge of local network topology, it does not make a decision to control the communication range by itself. Instead, the layer simply notifies the MAC protocol of the signal reception information including AOA and reception power, and lets the higher layers decide which nodes to communicate with. The physical layer normalizes the directional reception power based on the omnidirectional reception before notifying the MAC protocol such that higher layers do not need to know how the signal is received.

3.2 Link Selection Criteria (MAC)

3.2.1 *Link classification*

At the MAC sub-layer, each node maintains a cache table to keep the AOA, reception time and reception power of the last signal from each neighboring node. Among these pieces of information, the reception power is used to classify nodes and links in ARC, as it can deduce the path loss when the transmission power is constant. If the reception power from the physical layer is greater than *RXT*, the transmitter and the corresponding link are regarded as a *nearby* node and a *regular* link respectively. If the reception power is between *RXT* and *CST*, they are classified as a *faraway* node and an *extended* link, as the signals can be received only by directional reception.

The link classification in ARC is solely dependent on the reception power of signals, and not on the actual distance between two nodes. Unless network nodes actively exchange location information at the expense of additional traffic, distances to other nodes are difficult to measure, and are often misleading as the path loss is not simply a function of distance. Therefore, the use of path loss is effective for link classification as it inherently takes the environmental factors into account.

Please note that each node updates the AOA and reception time even when overhearing a signal transmitted to other nodes, but not the reception power. 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, overheard signals are not used to estimate the path loss from the transmitter and the node does not update the cache table on the reception power.

3.2.2 *Local network density*

ARC does not alter the protocol behaviors for communications through regular links, and only deals with extended links. The extended link selection in ARC is based on the local network density. ARC 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, ARC 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:

$$n_{all} \equiv n(0, 360), \qquad n_\theta \equiv n(\theta - D/2, \theta + D/2)$$

where θ is AOA from Node Y, and D is the angle of DNAV used in DVCS [13] at Node X as described in the related work section.

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 [5], directional antennas could leak rather large amount of energy in directions other than the transmission 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 that 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, as faraway nodes incur less interference and the node does not set DNAVs for overheard frames from faraway nodes.

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

$$\text{Condition (Omni): } n_{all} \leq M, \quad \text{(Directional): } n_\theta = 0$$

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 ARC 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 do 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 4.3.3 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 ARC 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 ARC performance. In this study, ARC is evaluated using QualNet [9], which supports simulation of directional antenna communications with a rich set of higher layer protocols. Table 1 lists a set of parameters not described in other sections but used to configure the corresponding layers in the study.

Table 1: Set of parameters used in the simulation study

Physical Layer Parameters	
Channel frequency	2.4 [GHz]
Signal reception	BER based
Data rate	2 [Mbps]
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.

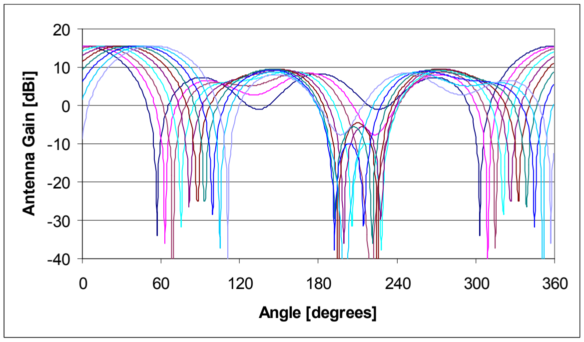


Figure 2: Antenna patterns for different directions

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 2. 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 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.

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* is set to –91 dBm equal to *CST*, which shows the network performance with a wide but fixed communication range.

- DA-ARC (Directional Antenna with ARC)

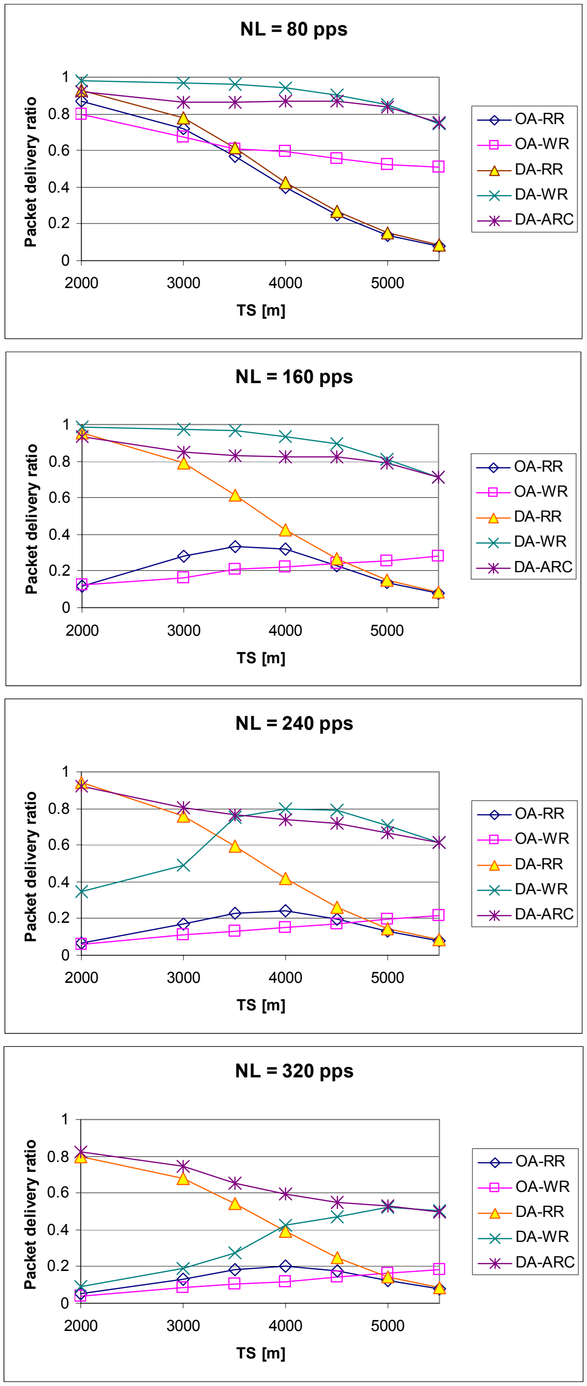
DA-ARC uses ARC to control the communication range, and it is the configuration to be evaluated in this study. Unless otherwise noted, ARC utilizes the directional reception condition only for the RREQs, which yielded the best performance among several variations as shown in Section 4.3.3.

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 DA-ARC node configurations examined later, this entire simulation study consists of nearly 4,000 simulation runs.

4.3 Simulation Results

4.3.1 Packet Delivery with Varied Density

Four charts in Figure 3 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-ARC closely follows DA-WR. At *TS* = 5500 m, both DA-WR (PDR: 0.75) and DA-ARC (PDR: 0.73) delivers almost 9 times more packets than DA-RR (PDR: 0.08) by preventing network partitions.


NL = 80 pps

NL = 160 pps

NL = 240 pps

NL = 320 pps

Figure 3: PDRs with varied terrain size

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 is 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 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 DA-ARC 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. DA-ARC 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.

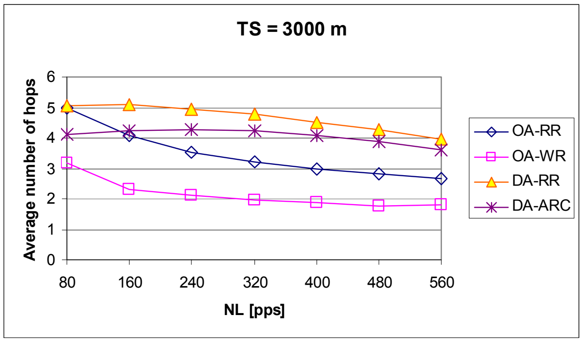
The last chart for *NL* = 320 pps holds the same trends seen at *NL* = 240 pps, with DA-WR degrading its performance further and yielding only less than 0.1 PDR at *TS* = 2000 m. On the other hand, DA-ARC does not degrade its performance much even at this network load for both dense and sparse networks,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

4.3.2 Hop Count and End-to-End Delay

Figure 4 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. When all node configurations are compared at fixed density, 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 DA-ARC have the same trend with the former slightly lower than the latter. As shown in the first chart, both OA-WR and DA-ARC 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.

DA-ARC, on the other hand, successfully reduces both hop count and end-to-end delay, as it avoids the use of unreliable extended links when setting up routes. As long as extended links used on the routes are robust, they can reduce the number of hops to destinations without increasing the average end-to-end delay.



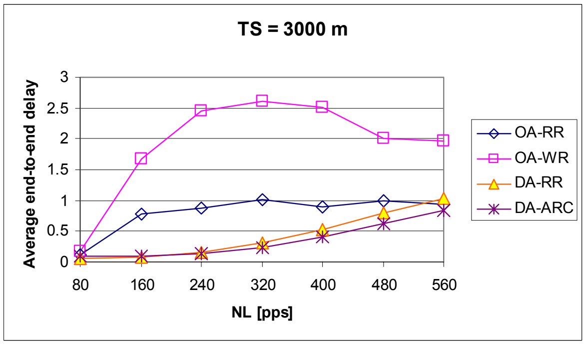
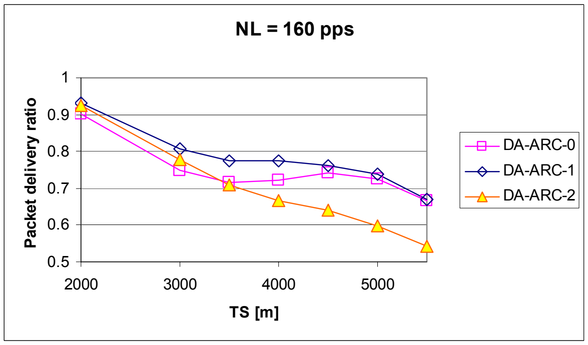


Figure 4: Average hop count and end-to-end delay

4.3.3 Link Selection Conditions

This subsection examines the effects of reception conditions used at each side of extended link on the overall network performance. Figure 5 shows the PDRs and the number of link breaks per second at *NL* = 160 pps with different reception conditions for ARC 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 DA-ARC variations:

- DA-ARC-0: it does not use the directional condition for either direction of the link.
- DA-ARC-1: it uses the directional condition for the direction of RREQs (application data) but not for the reverse direction.
- DA-ARC-2: it uses the directional condition for both directions of the link.
- Among these variations, the DA-ARC performance shown so far is DA-ARC-1. DA-ARC-0 and DA-ARC-2 use the same reception condition for both directions of each extended link, and are more aggressive or conservative than DA-ARC-1 in including extended links in the routes.



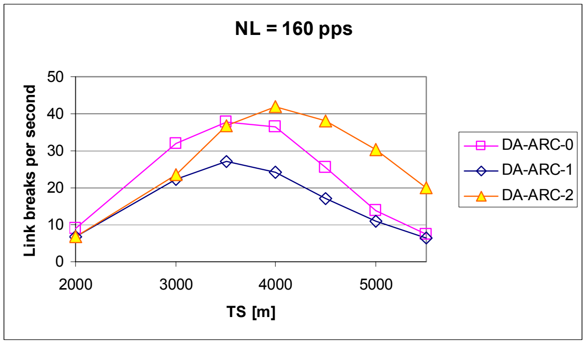


Figure 5: PDRs and link breakage frequencies with different reception conditions

As shown in the first chart, DA-ARC-1 achieves the best performance among these three for all terrain sizes. DA-ARC-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, DA-ARC-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. 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 5 shows the effects of many RREP message drops with DA-ARC-2. Please note that a RREP message dropped by the ARC link selection is counted as one link break in the statistics. As shown, DA-ARC-2 has the highest number of link breaks among them for sparse network cases despite of its strict reception conditions. DA-ARC-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.

5. CONCLUSIONS

This paper has presented ARC (Adaptive Range Control), a communication range control mechanism using directional antennas to be implemented across multiple layers. ARC 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 ARC for varied network densities and traffic loads. ARC 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 investigation on the use of directional antennas in MANETs is to be made. In this study, ARC 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, ARC 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 ARC, which is our future work.

6. ACKNOWLEDGMENTS

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