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Improving end-to-end communication by novel methodology of route quality approximation

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ABSTRACT
With the number of wireless smart devices growing rapidly due to the constant technological advances and product availability, significant effort has been put into optimizing their functioning to achieve the best possible performance. Using a wireless device usually implies them having an integrated power supply, and often without a possibility of recharging it. To mitigate the devices running out of power too soon, there is a myriad of developed approaches. One of the approaches is to use a low-consumption data exchange protocol, such as Zigbee that relies on the short-range devices to construct a wireless personal area network and use it to relay messages. To route packages through the network, the Zigbee protocol uses the ad-hoc on-demand distant vector routing protocol. In this paper, we analyse two new versions of a modified ad-hoc on-demand distant vector routing protocol that define routes by maximizing a route quality measure based upon aggregated link quality approximations.

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Mesh networks; mobile ad hoc networks; quality of service; routing protocols; Zigbee

Introduction

Smart wireless devices, commonly put under a unifying alias "Internet of Things" have been in focus of both the mainstream media and bleeding-edge scientific research for some time now [1], making it a valuable technology in day-to-day life [2]. Their reach, ranging from wireless sensor networks that collect and aggregate various forms of data in public and private spaces, to smart home solutions that give the user remote access to control and monitor common household devices, has been growing rapidly, both due to the increase in number of such devices and their integration complexity.

Usually, one such device makes for only a part of the whole system, playing a small and unique role, thus enforcing the importance of interconnectivity, effectively mandating the existence of a network, bridging the gap between distant elements, usually as a part of a wireless network [3], regularly in self-configuring environments devoid of human interaction [4], such as sensor network [5]. One solution is to connect all of the devices using a single wireless communication protocol, such as Zigbee [6], a protocol that has been tested extensively for scientific research [7], but also in real-world environments [8]. The Zigbee protocol is designed to work in Mobile Ad-hoc Networks (MANET) and uses the Ad-hoc On-demand Distant Vector (AODV) routing protocol [9,10] to construct the paths for the messages to follow, while travelling from the source to the destination device, in a unicast transmission communication process. The messages usually make several hops through intermediate devices [11] before reaching their destination, thus eliminating the need for direct device-to-device communication that would require powerful transmitters and receivers, increasing overall energy consumption [12]. These networks, albeit robust and flexible, are prone to problems with transmission synchronization [13].

While both specification and implementation of the AODV routing protocol are simple, making it very robust, they reduce the ability of adapting to varying conditions of a live network. When a device needs to send a message to a distant device, it uses AODV to determine a path through the network through which messages can be relayed. To do so, the source device broadcasts a route request to the destination device, and waits for an answer. As soon as an answer is successfully received, the route is established and the messages start flowing.

One of the problems of this approach is that the final route is defined largely by the time with which the devices can process incoming messages used during AODV execution. This renders concepts such as load balancing impossible to implement and may lead to problems of overusing specific devices for routing purposes, increasing their energy consumption and reducing lifetime. Multiple modifications to AODV have been proposed [14] in an effort to resolve this issue, ranging from those based on modifying protocol

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parameters across the technology stack [15] tracking dynamic Quality of Service (QoS) measurements [16] or simply reducing the complexity [17]. One approach is to search for an alternative route better suited to our needs. Having this in mind, the idea of route preference or route quality seems reasonable. By defining the route preference to be higher for routes consisting of rarely used devices, one can devise a route protocol that chooses routes based on their preference. This approach has already been proposed before. The work of Periyasamy and Karthikeyan proposes a Link-Quality Based Multipath Routing (LQBMR) protocol [18] based on Path-Link Quality Estimator (P-LQE), a protocol that is an extension to the Ad-hoc On-demand Multipath Distant Vector (AOMDV) routing protocol. Machado et al. propose an energy-based routing protocol [19] for use in both small and large-scale networks. Balaji and Duraisamy propose a modification of the AODV protocol based on Ant Colony Optimization (ACO) [20], a technique derived from ant behaviour. Tsai et al. propose a modification based on smoothed signal-to-noise ratio [21], similar to that proposed in this work. Akhter and Sanguankotchakorn propose a modification based on predefined QoS restrictions [22]. Additionally, a number of similar approaches that specifically target energy consumption reduction have been proposed. The work of Farhan et al. proposes the LQOR routing protocol that incorporates the transmission of remaining energy levels to neighbouring nodes in an effort to increase performance [23]. Kirubasri et al. propose the EEPLQRR routing protocol that increases performance by predicting the link quality in terms of remaining node's energy [24]. The work of Singh and Kalla proposes the EACAR-LM routing protocol that uses the total cost function based on the received signal power, remaining node energy and congestion status in the route discovery phase [25].

Extending the AODV protocol

Our two approaches are both special instances of the Bijective Link-Quality Aggregation AODV (BLQA-AODV) protocol [26]. The BLQA-AODV protocol defines a route quality – a value assigned to each individual route using the quality function $Q(\cdot)$, denoting our preference to choosing that route as the solution to the routing problem. The route quality function is defined to be the aggregated link quality of all single-hop routes it comprises of. In our case, the aggregation operator is defined as arithmetic multiplication, defining the route approximation to be

$$Q(n_1 \dashrightarrow n_i \dashrightarrow n_N) = \prod_{i=1}^{N-1} q(n_i \rightarrow n_{i+1}) \qquad (1)$$

Here, $n_1 \dashrightarrow n_i \dashrightarrow n_N$ denotes the route from a source device n_1 to the destination device n_N through a routing device n_i, and the link quality function that approximates the single-hop route quality function is denoted with $q(\cdot)$. While the BLQA-AODV protocol does not assume that

$$q(n_a \rightarrow n_b) \equiv q(n_b \rightarrow n_a) \qquad (2)$$

defining the link quality approximation to be invertible, we tested the impact of this constraint by implementing both cases.

Implementing BLQA-AODV with invertible link quality approximation

Finding a route using AODV comprises of two stages, the request stage in which a route request (RREQ) is broadcasted from device to device, containing relevant information, such as the address of the source device that initiated the RREQ, and the destination device with which it wishes to communicate. Once the route request reaches the destination device of the RREQ or an intermediate device that already has a valid route to the destination, a route reply (RREP) is sent via the inverse route that was just established. This means that each of the routing devices upon receiving a RREQ defines an inverse route to the source device using the neighbour device it received the RREQ from as the next hop. Doing so ensures that once this device receives a RREP, it already has a route with which it can send the reply to the RREQ source device.

To implement the non-restrained BLQA-AODV (nrBLQA-AODV), the RREQ packets are expanded with the addition of the aggregated route quality from the source device n_S to the neighbouring device n_P, that is $Q(n_S \dashrightarrow n_P)$. Once a routing device n_T receives a RREQ, it approximates the route quality as

$$Q(n_S \dashrightarrow n_P \rightarrow n_T) \cong Q(n_S \dashrightarrow n_P) \cdot q(n_P \rightarrow n_T) \qquad (3)$$

In contrast to AODV that dismisses repeated broadcasted RREQ packets for the same route after receiving the first RREQ, the BLQA-AODV must repeat the broadcast if the approximated route quality of the new RREQ exceeds all previously received ones. This ensures notifying sequential routing devices of a potential route with a higher quality. To avoid unnecessary routing overhead, the approximated route quality associated with a RREQ packet is stored with the broadcast data defined by the AODV protocol. This enables the BLQA-AODV to dismiss any RREQ packet that contains an approximated route quality smaller of equal to the maximum one received by a device, thus reducing unnecessary routing overhead, as well as to update the associated information if a RREQ packet is received with an approximated route quality higher that all previously received.

With each broadcasted RREQ packet, an inverse route is added. This route is used to send a potential future RREP packet to the source device. To ensure that any future route requests are correctly processed, an approximated quality is assigned to the inverse route, defined as

$$Q(n_T \rightarrow n_P \overset{\dots}{\rightarrow} n_S) \cong Q(n_S \overset{\dots}{\rightarrow} n_P \rightarrow n_T) \tag{4}$$

With this, the value representing the link quality approximation $q(n_T \rightarrow n_P) \cong q(n_P \rightarrow n_T)$ is stored with the route as well.

In the case of reaching the destination device or a device with an existing valid route to the destination device, a RREP is sent back to the source device. To enable the devices, thereon representing the constituents of the route, of comparing routes via approximated route qualities, each RREP contains the aggregated route quality constructed in the same manner as the aggregated route quality in each RREQ. After a device receives a RREP, the quality contained in the packet represents the approximated quality of route $n_T \overset{\dots}{\rightarrow} n_P$. Before forwarding the RREP, the device updates the approximated quality so that it represents the same value for the device receiving it, using the link quality approximation obtained in the first stage, as

$$Q(n_P \rightarrow n_T \overset{\dots}{\rightarrow} n_D) \cong q(n_P \rightarrow n_T) \cdot Q(n_T \overset{\dots}{\rightarrow} n_D) \tag{5}$$

If the device originally sending the RREP is the destination device, it initializes this value to be 1, and if it is a device that has a valid route to the destination device, it initializes the approximated route quality value to be the value of its valid route to the destination device, before following the process described with (5).

Implementing BLQA-AODV without invertible link quality approximation

Implementing the restrained BLQA-AODV (rBLQA-AODV) where the equivalence (2) does not hold implies that inverse routes cannot get an approximated route quality at that time since (4) does not hold. Therefore, in this implementation, the inverse routes get a symbolic approximated route quality of zero. Consequentially, when a device with a valid route to the destination with approximated route quality of zero receives a RREQ, it sends the RREP with approximated route quality of zero to the source device, but also broadcasts the RREQ. This ensures that the source device gets a route as soon as possible, but also eventually gets the best route available.

Another important difference to the nrBLQA-AODV implementation is that the address of the next hop when sending RREP packets is not contained in the routing table, but in the list of received RREQ broadcasted in the first stage. This is to enable multiple asynchronous active route searching processes, which demand a separate list of route requests to the routing table itself.

Simulation results

Both the restrained and the non-restrained implementations of the BLQA-AODV protocols rely on the definition of the link-quality approximation function $q(\cdot)$ to enable the calculations needed for a simulation environment, thus effectively defining distinct and separate routing protocols. To form these functions, we took advantage of indicators commonly used to determine link quality, the Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR). In addition, for the restrained BLQA-AODV protocol, we used the device's remaining energy level, targeting the possibility of using this indicator to form routes that do not strain devices low on energy. In order to construct a collection of potential link-quality functions using these indicators, we devised three simple approaches and a condition of proportionality of the link-quality function value with all of the indicators were set, implying that with the increase in value of the indicators, the value of the link-quality function should also increase. To achieve this, we combined the indicators using either multiplication, the $\max(\cdot)$ function or the $\min(\cdot)$ function. The approach of combination via multiplication has the effect of constructing a link-quality function that decreases in value with the decrease of any indicator value. On the other hand, the approach of combination via the use of the $\max(\cdot)$ value has the "optimistic" effect of treating two links to be of equal quality, disregarding other indicators. Alternatively, the approach that uses the $\min(\cdot)$ function has the "pessimistic" effect of disregarding indicators with high values and only using the lowest one. Lastly, such constructions were could also be limited in the maximum value they produce in order to ensure the approximated route quality functions are always decreasing.

Using these approaches, functions (6)–(15) where formed as the link quality approximation for both implementations of the routing protocol.

$$q(n_P \rightarrow n_T) \equiv q(l) =$$

$$snr(l) \tag{6}$$

$$rssi(l) \tag{7}$$

$$L(snr(l)) \tag{8}$$

$$L(rssi(l)) \tag{9}$$

$$snr(l) \cdot rssi(l) \tag{10}$$

$$L(snr(l) \cdot rssi(l)) \tag{11}$$

$$\max(snr(l), rssi(l)) \tag{12}$$

$$L(max(snr(l), rssi(l))) \tag{13}$$

$$\min(snr(l), rssi(l)) \tag{14}$$

$$L(\min(snr(l), rssi(l))) \tag{15}$$

Alongside these, an additional number of functions were constructed for use with the restrained implementation of BLQA-AODV, using the node remaining energy level, giving formulas (16)–(35).

$$q(n_P \rightarrow n_T) \equiv q(l) =$$

$$e(n_T) \tag{16}$$

$$L(e(n_T)) \tag{17}$$

$$e(n_T) \cdot snr(l) \tag{18}$$

$$e(n_T) \cdot rssi(l) \tag{19}$$

$$L(e(n_T) \cdot snr(l)) \tag{20}$$

$$L(e(n_T) \cdot rssi(l)) \tag{21}$$

$$\max(e(n_T), snr(l)) \tag{22}$$

$$\max(e(n_T), rssi(l)) \tag{23}$$

$$\min(e(n_T), snr(l)) \tag{24}$$

$$\min(e(n_T), rssi(l)) \tag{25}$$

$$L(\max(e(n_T), snr(l))) \tag{26}$$

$$L(\max(e(n_T), rssi(l))) \tag{27}$$

$$L(\min(e(n_T), snr(l))) \tag{28}$$

$$L(\min(e(n_T), rssi(l))) \tag{29}$$

$$e(n_T) \cdot snr(l) \cdot rssi(l) \tag{30}$$

$$L(e(n_T) \cdot snr(l) \cdot rssi(l)) \tag{31}$$

$$\max(e(n_T), snr(l), rssi(l)) \tag{32}$$

$$L(\max(e(n_T), snr(l), rssi(l))) \tag{33}$$

$$\min(e(n_T), snr(l), rssi(l)) \tag{34}$$

$$L(\min(e(n_T), snr(l), rssi(l))) \tag{35}$$

In both of these cases, $\mathrm{snr}(l) = \mathrm{snr}(n_P \rightarrow n_T)$ is the signal-to-noise ratio of a packet begin sent through link $n_P \rightarrow n_T$ scaled to take values between 0 and 1, $\mathrm{rssi}(l) = \mathrm{rssi}(n_P \rightarrow n_T)$ is the received signal strength indicator of a packet begin sent through link $n_P \rightarrow n_T$ scaled to take values between 0 and 1, and $L(\cdot)$ is a range-limiting function defined as $L(x) = \min(\max(x, 0), 0.99999)$. In the case of the restrained BLQA-AODV algorithm, $e(n_T)$ is the current energy level of the device n_T scaled to take values between 0 and 1.

Table 1. Simulation configuration parameters used for executing the NS2 simulations.

Parameter	Value
Channel type	WirelessChannel
Radio-propagation model	TwoRayGround
Network interface	WirelessPhy/802_15_4
Media access control	Mac/802_15_4
Interface queue type	LL
Antenna model	OmniAntenna
Antenna height	1.5 m
Interface queue type	PriQueue
Max packets in IFQ	150 packets
Routing protocol	AODV, BLQA-AODV (restrained and non-restrained)
Number of FFDs	10–25
Number of RFDs	2, 5, 8, 11, 14, 17 or 20
Transmitter power	0.28183815 W
Topography size	1000 m × 1000 m
Carrier sense threshold	9.21756×10^{-11} W (550 m)
Receive threshold	3.65262×10^{-10} W (250 m)
Capture threshold	10 dB
Operation frequency	$9.14 \times 10^{+8}$ Hz
Transmit power	3.132×10^{-2} W
Receive power	3.528×10^{-2} W
Idle power	7.12×10^{-4} W
Sleep power	1.44×10^{-9} W
Energy model	EnergyModel
Initial Energy	100 J
Simulation time	3600 s
Number of CBR links	2, 5, 8, 11, 14, 17 or 20
CBR packet size	70 bytes
CBR interval	2 s

To measure how the implemented routing protocols behave, the Network Simulator 2 (ns-2.35) tool was used. It comes with an implementation of IEEE 802.15.4 standard, as well as an implementation of AODV routing protocol. To estimate the QoS measurements, we designed a number of experiments, based on a variable number of communication links between Reduced-Function Devices (RFD) and a Personal Area Network (PAN) coordinator within a MANET network of a variable number of full-function devices (FFD). The PAN coordinator was placed in the centre of a 1000 m × 1000 m area. Along with it, a varying number of RFDs, ranging from 2 to 20 with a change step of 3, and a varying number of FFDs, ranging from 10 to 25 with a change step of 1. Each of the RFDs produced a CBR data transmission to the PAN coordinator at an interval of 2 seconds sending packets of size 50 bytes and the simulation time was 3,600 seconds (1 hour). Table 1 contains a summary of the configuration parameters used while executing the NS2 simulations.

Each of the 112 different simulation scenarios, defined uniquely by the number of placed FFDs and RFDs was simulated 50 times, both for the restrained and non-restrained BLQA-AODV routing protocol implementation, for each of the appropriate link-quality approximation functions $q(\cdot)$. This gives a total number of 61,600 simulations for the non-restrained BLQA-AODV routing protocol, and 173,600 simulations for the restrained BLQA-AODV routing protocol. With an average real-time execution of 14.2 seconds per simulation, the total real-time invested in executing all

Table 2. Comparison of QoS measurements between AODV and nrBLQA-AODV with various $q(\cdot)$.

$q(l)$	Received packets	End-to-end delay (ms)	Throughput (bit/ms)	Consumed energy (J)	Sent routing packets
AODV	7964	77.55	1.25431	115.67	3814
(6)	7768	82.53	1.22340	117.25	4025
(7)	7777	84.06	1.22481	118.52	4046
(8)	7767	87.88	1.22327	117.15	3986
(9)	7783	84.49	1.22584	118.59	4015
(10)	7693	71.70	1.21172	119.57	4101
(11)	7711	72.40	1.21450	119.66	4109
(12)	7866	81.65	1.23888	116.19	3938
(13)	7870	78.12	1.23960	116.27	3947
(14)	7690	70.95	1.21110	119.52	4113
(15)	7704	71.44	1.21334	119.53	4075

the simulations on a single-thread CPU would amount to over 36.8 days. To mitigate this, the simulations were executed on a distributed network of computers, ranging in size between 20 and 30 computers, depending on availability, giving an average of 55 processor cores available at any given time and reducing the needed execution time to 16.24 hours.

The QoS measurements gathered in the simulations and used for comparison are [27–29]:

- *Received packets* – the average number of received CBR packets
- *End-to-end delay* – the average end-to-end delay in milliseconds
- *Throughput* – the average number of bits transmitted per millisecond
- *Consumed energy* – the average energy difference of the total network energy at the start and end of the simulation
- *Sent routing packets* – the average number of sent routing packets

As shown in Table 2, using nrBLQA-AODV routing does not produce results unequivocally better results than using AODV. The only QoS measurement that gives better results is the average end-to-end delay when using the link-quality approximation functions (10), (11), (14) and (15). All of these functions have an effect of approximating the link-quality in terms of the worst-case scenario between the RSSI and SNR values. We hypothesize this has the effect of choosing routes that have less chance of dropping the packets, thus leading to the decrease in measured end-to-end delay. However, the effect of prolonged route search due to additional sent routing packets counters this positive trend and leads to an overall smaller average number of received packets in the end.

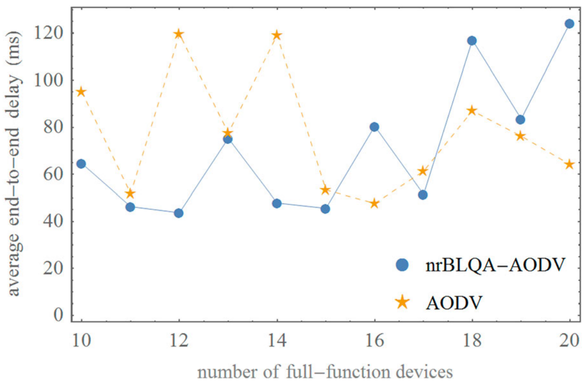

Figure 1. Average end-to-end delay by number of FFDs for $q(n_P \to n_T) = \min(snr(n_P \to n_T), rssi(n_P \to n_T))$.

The decrease in average measured end-to-end delay for nrBLQA-AODV when using (14) as the link-quality approximation function comes from simulations with fewer numbers of nodes. We have chosen to visualize the dependency of the average end-to-end delay for that specific choice of the link-quality function because that is the case in which the best results for the average end-to-end delay measurement were obtained. In addition, this specific function has the property of equating to the "worst-case scenario" for evaluating link quality since it uses the minimum between the relative value of SNR and RSSI as its link-quality assessment. As can be seen in Figure 1, the average end-to-end delay tends to increase for the nrBLQA-AODV routing protocol when using (14) as the link-quality function as the number of full-function devices increases. We hypothesize that in such scenarios the RSSI and SNR values used for the route search algorithm are better approximation of current state of link-quality than the long-term state, upon which the measured QoS depends on. It is possible that applying a smoothing function on the RSSI and SNR values over time and using them as input for the link-quality approximation function would produce better results. Alternatively, we can see that the same trend does not continue on Figure 2 and that the average delay for the nrBLQA-AODV routing protocol when using (14) as the link-quality function does not increase for larger RFDs. This is as expected since the RFDs do not participate in the routing of data, but only generate them, so increasing the number of said devices should not play a role in the average end-to-end delay measurement, unless a critical number of RFDs is introduced and the network becomes saturated. However, the number of devices present in our simulations of far lower than said limit, so this is not the result.

In contrast to using the non-restrained implementation of the BLQA-AODV protocol, the restrained version gives better results for all used link-quality approximation functions. Figure 3 clearly shows that the rBLQA-AODV with (16) as the link-quality function outperforms AODV as the number of FFDs increases. The steady increase of the average packet delivery ratio seen for both protocols is attributed to the fact that in those situations the number of packets remains constant while the number of devices capable of routing said packets increases, thus reducing the possibility of

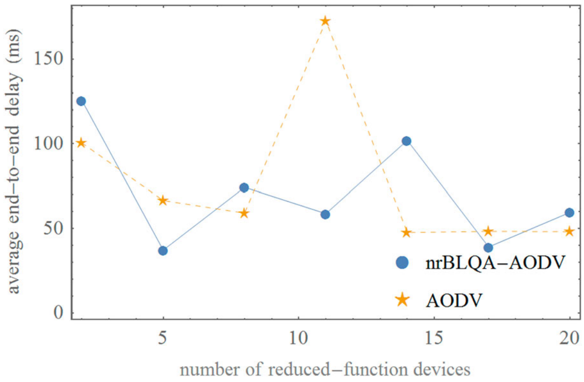

Figure 2. Average end-to-end delay by number of RFDs for $q(n_P \to n_T) = \min(snr(n_P \to n_T), rssi(n_P \to n_T))$.

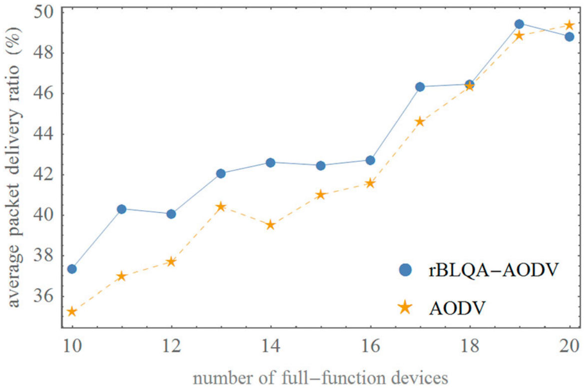

Figure 3. Average packet delivery ratio by number of FFDs for $q(n_P \to n_T) = e(n_T)$.

dropping them, but the rBLQA-AODV routing protocol produces comparably better results. The opposite trend can be seen in Figure 4 where the average packet delivery ratio decreases with the increasing number of RFDs since the number of packets to be transferred increases proportionally as well. However, even here the rBLQA-AODV outperforms AODV by a few percentage points. We can see from Figure 5 that restraining the BLQA-AODV routing protocol resolves the issue of increasing average end-to-end delay for higher numbers of FFDs that was observed in Figure 1. As for the average end-to-end delay with increasing RFDs that is shown in Figure 6, rBLQA-AODV with (16) as the link-quality function outperforms both AODV and its non-reduced counterpart remaining more-or-less constant throughout.

The difference in displayed QoS measurements between the restrained and non-restrained implementations of the BLQA-AODV protocol is aligned with our hypothesis that assuming (2), the errors introduced in the aggregated route quality approximation overcome the benefit choosing a route based on that quality. This explanation is further affirmed by acknowledging the fact that nrBLQA-AODV implementation does give better results than AODV, but only in simulations with fewer FFD devices where the accumulated error is small enough.

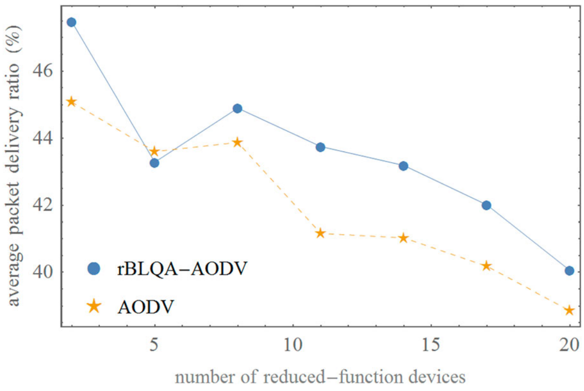

Figure 4. Average packet delivery ratio by number of RFDs for $q(n_P \to n_T) = e(n_T)$.

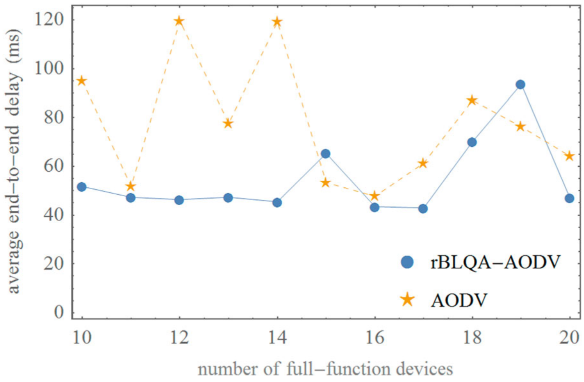

Figure 5. Average end-to-end delay by number of FFDs for $q(n_P \to n_T) = e(n_T)$.

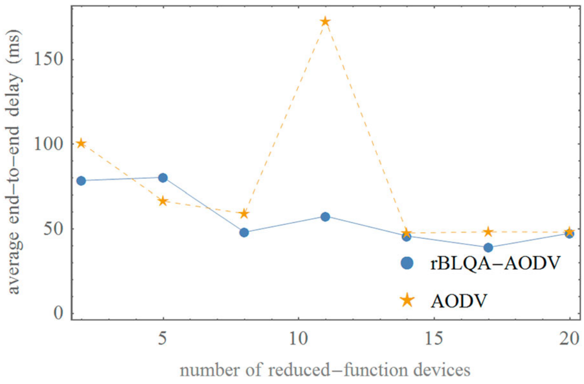

Figure 6. Average end-to-end delay by number of RFDs for $q(n_P \to n_T) = e(n_T)$.

As for the rBLQA-AODV, we can see that the approach by which the routes are chosen in itself produces improved results in contrast to using AODV, but choosing a metric to approximate the link-quality plays a major role in the final performance boost. We can see from Table 3 that for some link-quality approximation functions $q(\cdot)$ the end-to-end delay is reduced up to 30%, but with an energy consumption increase of 2.1%, which is in line with other such results [30,31], if not better [32,33].

It is also interesting to see that in some cases the routing overhead is decreased as well, albeit by a small

Table 3. Comparison of QoS measurements between AODV and rBLQA-AODV with various $q(\cdot)$.

$q(l)$	Received packets	End-to-end delay (ms)	Throughput (bit/ms)	Consumed energy (J)	Sent routing packets
AODV	7964	77.23	1.25431	115.67	3814
(6)	8182	72.17	1.28858	120.82	3824
(7)	8107	60.29	1.27685	121.50	3904
(8)	8175	80.65	1.28751	120.64	3826
(9)	8106	60.38	1.27665	121.28	3913
(10)	8045	54.43	1.26695	123.05	4011
(11)	8036	54.30	1.26548	122.88	4036
(12)	8223	51.89	1.29503	119.23	3805
(13)	8241	51.04	1.29796	119.30	3782
(14)	8039	62.39	1.26595	123.03	4036
(15)	8016	62.44	1.26232	122.80	4022
(16)	8304	54.61	1.30785	118.06	3690
(17)	8304	54.61	1.30785	118.06	3690
(18)	8254	70.29	1.30004	118.87	3686
(19)	8069	62.63	1.27075	121.09	3895
(20)	8254	70.29	1.30004	118.87	3686
(21)	8069	62.63	1.27075	121.09	3895
(22)	8128	82.03	1.28008	119.74	3855
(23)	8111	59.02	1.27740	121.42	3930
(24)	8281	56.75	1.30418	119.05	3691
(25)	8079	62.78	1.27228	121.20	3880
(26)	8171	64.50	1.28684	120.08	3830
(27)	8135	64.70	1.28126	121.19	3908
(28)	8281	56.75	1.30418	119.05	3691
(29)	8079	62.78	1.27228	121.20	3880
(30)	8081	56.61	1.27265	121.51	3865
(31)	8081	56.61	1.27265	121.51	3865
(32)	8273	51.72	1.30297	119.54	3725
(33)	8254	51.92	1.30005	119.27	3761
(34)	8070	56.88	1.27098	121.29	3939
(35)	8070	56.88	1.27098	121.29	3939

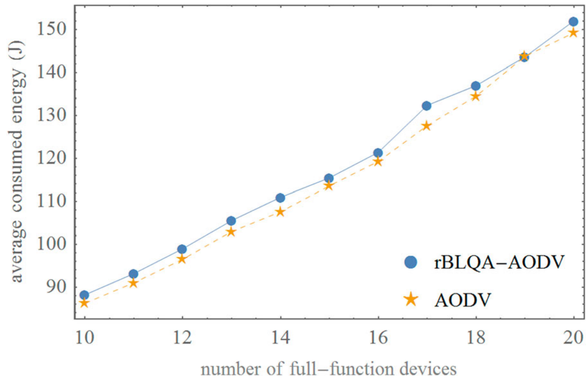

Figure 7. Average consumed energy by number of FFDs for $q(n_P \to n_T) = e(n_T)$.

value of 3%. We hypothesize this reduction is due to the fact that fewer RREP packets are being lost while being sent through unreliable inverse routes, thus reducing the number of required resending of the initial RREQ packets. Lastly, we can see in Figures 7 and 8 how the rBLQA-AODV with (16) as the link-quality function is outperformed in terms of average energy consumption.

Conclusion

We have shown that the non-restrained BLQA-AODV routing protocol, based on the assumption that the quality of communication via a link does not change depending on the transmission direction, does not outperform AODV in any QoS measurement other than average end-to-end delay. On the other hand, we have also shown that the restrained BLQA-AODV routing protocol, that does not make said assumption, outperforms AODV for a variety of link-quality function approximations, but is still highly dependent on the specific link-quality function choice. Since the implementation of the restrained BLQA-AODV gave far better results than the implementation of the non-restrained BLQA-AODV, we suggest focusing on that protocol for future research.

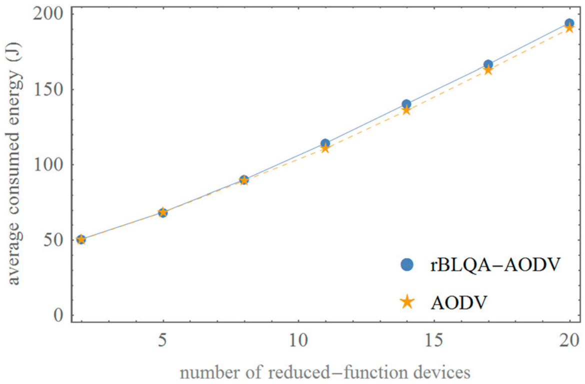

Figure 8. Average consumed energy by number of FFDs for $q(n_P \to n_T) = e(n_T)$.

Future research

For future research, we plan focusing on different, more complex constructions of link-quality functions in an effort to maximize the approximated QoS measurements. We plan to repeat the simulations by using an extensive list of link-quality functions $q(\cdot)$ constructed as linear combinations of $snr(n_P \to n_T)$, $rssi(n_P \to n_T)$ and $e(n_P)$. Going a step further, a whole array of utilities could be used to construct link-quality functions of event greater complexity, such as various heuristic approaches like genetic algorithms and genetic programming, or more advanced ones like artificial neural networks that have seen a significant performance boost in recent years.

Disclosure statement

No potential conflict of interest was reported by the authors.

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