Game-theoretical Relay Selection Strategy for Geographic Routing in Multi-hop WSNs

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***Abstract*— This contribution proposes and investigates a random access Medium Access Control (MAC) – Relay Selection Mechanism – for cluster-based geographic routing in Multi-hop Wireless Sensor Networks (WSNs). The intertwined MAC and network routing solution is derived in a cross-layer approach. The game-theoretical relay selection strategy (random multiple access) relies on well-known descending pricing auctions also known as "Dutch Auctions". In particular, successive rounds of Dutch auctions are employed to deal with contention avoidance and contention resolution stages of the non-cooperative games between source and relay nodes. If a non-empty auction round has no winner (due to collision), the source starts a new round with a signaling packet containing an indication of collision. Consequently, at each round relay candidates are able to infer on their location relative to other potential relays, based on which they can choose to drop out or continue their bidding. The strategy, which is fully distributed and eliminates the need for the source to know the number of potential relays *a priori*, proves very efficient, approaching the performance of an ideal scheduled-based Random Selection Algorithm (RSA). The performance of our previously proposed cluster-based geographic routing employing this RSA is investigated using an event-driven network simulation, in a scenario with a topological dead-end hole. The results indicate that the combined techniques can retain a substantial portion of the Packet Delivery Success Ratio (PDSR) associated with a system with perfect relay selection.**

I. Introduction

In WSNs, especially those of larger scale, employing hundreds or thousands of sensors (nodes), information exchange between sensors separated by distances exceeding radio range requires packets to be routed through a chain of relays towards a destination [1]. In such multi-hop networks, where nodes have knowledge of their location relative to one another, even if not exact, greedy geographic routing is an effective technique to autonomously and efficiently route packets through the network [1]. Unfortunately, a well-known problem of simple greedy geographic routing is that packets may be lost if anywhere along the multi-hop path of a packet towards a destination a relay in the forwarding direction cannot be found (dead-ends).

In [2], a clusterization mechanism for geographic routing in WSNs was proposed. The underlying tessellation procedure to cluster network provides robustness to dead-ends. The proposed cluster-based routing protocol is composed of two operational parts: global routing among adjacent clusters and localized relay-selection inside clusters. However, no explicit Contention Resolution (CR) mechanism for the cluster-based solution was used since the objective is to evaluate the routing technique only.

In Random Multiple-Access (RMA) networks (essentially contention-based), nodes are continuously competing to access the shared channel in a non-cooperative game [3]. In such networks, contention-based channel access protocols are the natural choice (e.g. ALOHA, Carrier Sense Multiple Access (CSMA) and thereof variations) to control access to the medium.

In this contribution we propose and investigate a MAC scheme which is based on game theoretical ideas and provides a suitable mechanism to perform relay selection in multi-hop WSNs. The overall solution interconnects Random Access (RA) MAC and Network geographic routing in a cross-layer approach.

The proposed game-theoretical relay selection strategy is indeed implemented as an iterative Dutch auction, where the "auctioneer" corresponds to the source node and "bidders" are the relay nodes [4]. In Dutch auctions, an auctioneer starts the process with a high asking-price which is lowered each iteration until some bidders accept the current price, or a pre-determined reserve price (minimum acceptable price) is reached. Dutch auctions are extremely convenient to sell goods – assignment of network resources – quickly. The reasons are two-fold, the auction ends with the very first bid and the auctioneer may set accordingly the decreasing rate of artifact value (depreciation rate) aiming at quickening the auction [5].

The remainder of this article is organized as follows. In section II the Relay Selection (RS) strategies are introduced, namely, ideal scheduled RSA, Capetanakis-Tsybakov-Mikhailov (CTM)-based RSA and the auction-based RS strategy. The simulation framework is detailed in section III. Additionally, the cluster-based routing protocol is succinctly presented. In section IV, the performance of the auction-based RS is evaluated. The overall performance of the intertwined MAC and network routing solution is also addressed. In section V we provide the conclusions and final remarks about the proposed auction-based RSA.

II. Random Access MAC - Relay Selection

In random multiple access channels, nodes continuously compete for accessing the shared physical medium. Many MAC protocols are available to dictate channel access: channelization methods, packet-oriented methods and hybrid versions. Typically, such protocols divide the channel assignment task into two distinct phases: (i) collision avoidance and (ii) collision resolution [3].

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In [2], no explicit CR mechanism was used since the objective is to evaluate the routing technique only. In this contribution, previous studies are extended by addressing the RMA problem in the context of multi-hop WSNs. More specifically, the relay selection mechanism is investigated.

The proposed solution deals with the collision avoidance/resolution stages by employing economic game-theoretical concepts. Typically, when a source node has a packet pending for transmission, a Request to Send (RTS)/ Clear To Send (CTS) handshake is triggered [6]. However, each suitable relay dwelling on the source node's radio range, which have received a RTS packet, will reply with a CTS packet and collisions may occur. Thus, an appropriate mechanism has to be employed in order to cope with imminent contention.

This contribution proposes the utilization of Dutch auctions as an effective alternative to address the RS process in conjunction with an RA-MAC solution. According to this proposal, source node plays the role of an auctioneer and potential relays are the bidders. The underlying concept is that players interacting in a non-cooperative game will follow the global strategy (Auction-based RSA) in order to maximize its own pay-off function in such a way that social welfare is guaranteed (optimal strategy). The price is derived from separation distance between source, relays and sink (similar to the greedy forwarding procedure).

After receiving a RTS packet, each relay node can decide independently whether or not it provides suitable forwarding conditions to the source towards the sink. Node that find themselves suitable to relay the packet bid by replying to the RTS packet. If collision occurs a new round of the auction starts including only the first round contenders or, alternatively, any well-known Q-ary splitting tree algorithm may be used [7]. The bidding process goes on and may demand several iterations (value depreciation) before the auction stops, though no actual signaling exchange among participant bidders is explicitly done. The network end-to-end packet delivery latency and overall energy consumption (social welfare) are expected to diminish, since the number of iterations in each single-hop relay selection is decreased.

The RS problem is addressed in this contribution by evaluating three distinct mechanisms – ideal scheduled RS strategy, Random access with CTM-based RSA and Auction-based RSA with location awareness – which are described subsequently.

A. Ideal Scheduled RS Strategy

The scheduled RSA is actually an idealized procedure that has been devised as the reference case to sort out the effectiveness of the proposed auction-based strategy. When there is a packet pending for transmission, the source node "ideally" schedules all neighbors that may operate as a suitable relay towards the destination assigning them distinct time-slots.

Figure 1 illustrates the scheduled RS mechanism with four potential relays (out of the total number of neighbors) in an appropriate condition to forward the packet[1].

[1]Nodes that are awake and not taking part in any other transaction

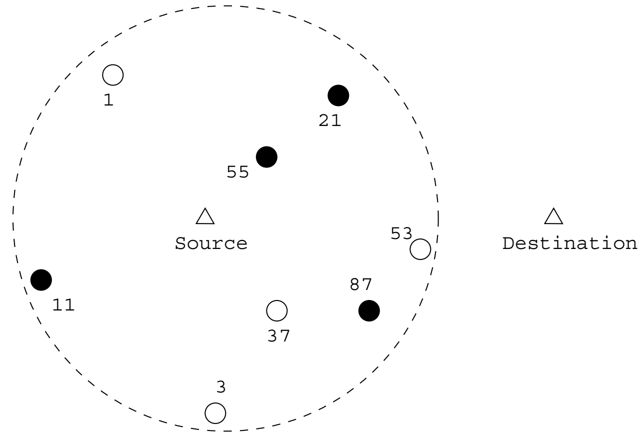

Fig. 1. Illustration of the scheduled RSA. Relay candidates are identified by filled-circles. The dashed circle delimits the source's radio range.

The source node instantaneously schedules all potential relays based on their IDs, which are stored in the source's neighborhood table[2]. For the illustration presented in figure 1, the source node schedules the potentials relays (nodes identified by filled circles) in the order $\{11, 21, 55, 87\}$. Relay candidates then reply with CTS messages enclosing their location sequentially. After receiving all the CTS messages from the potential relays, the source node then decides greedily the most suitable candidate, in this case 87 and finally forward the data packet. Indeed, by following this approach there is no collision at all since all relays have distinct time slots to reply.

B. CTM-based RS Strategy

For the RA method, the contention avoidance stage is performed using RTS/CTS handshake protocol [6], while the contention resolution stage is undertaken by employing simple splitting tree technique [7].

The Contention Resolution Algorithm (CRA) is based on a stack-based algorithm for RMA communications [8]. The algorithm provides a convenient implementation for the CTM protocol by having each potential relay maintain their own virtual stack independently. The CRA is implemented considering the Obvious Blocked Access Protocol (BAP) which means that no relay is allowed in the transaction once the contention has been initiated. During the contention resolution interval, a neighbor may become awake but it is not supposed to take part in the ongoing transaction [8]. Eventually, if no suitable relay is found in a given RS interaction, the source node goes to sleep and afterwards the connection may be restarted with new players.

In [7], the Q-ary CRA in RA system was extensively investigated: free and blocked access, binary and ternary feedback are considered in conjunction with Q-ary collision resolution algorithms. The authors showed that the CTM-based CRA presents a hard limitation on the maximum stable throughput that may still be tractable by the algorithm, therefore a key parameter for such system is the maximum admissible traffic.

[2]It is assumed that the neighborhood table is acquired during the discovery procedure.

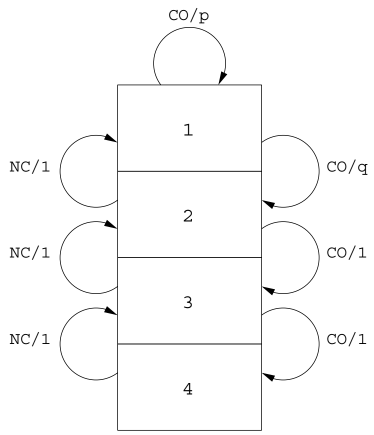

Fig. 2. Virtual stack-based CRA considering two levels of depth. Binary channel feedback is used {NC, CO} (no collision and collision) [8].

Figure 2 exemplifies the virtual stack-based CRA with two levels of depth [8]. All nodes start at stack level one. When the relay candidates listen to a RTS packet with indication of collision, nodes that have transmitted in the previous slot decide to retransmit or to refrain with complementary probabilities p and q, respectively. Nodes that have not transmitted – potential relays occupying a stack level higher than one – increase their stack level by one to make space to nodes entangled in the current collision. Conversely, when there is no collision (either an idle slot or successful transmission), the remaining nodes decrease their stack level.

Algorithm 1 Pseudo-code for the CTM-based RSA.

Require: Number of levels of the virtual stack.

Source Node initiates RTS/CTS handshake;
for all Neighbor nodes (potential relays) **do**
  if Node can propagate packet **then**
    Relay flips a "Q-sided coin".
    Relay replies if its stack level is one;
  end if
end for
if There is collision **then**
  Source Node sends notification to relay candidates;
  for all Neighbor nodes (potential relays) **do**
    if Node replied in the previous slot **then**
      Relay flips the "Q-sided coin" again;
      Relay replies if its stack level is one;
    else {Node did not reply previous slot}
      Relay increases its own stack level by $Q-1$;
    end if
  end for
else if There is one relay only **then**
  Relay in level one send CTS;
  Relays decrease their level by one;
else if There is no reply **then**
  Relays decrease their level by one;
  Source Node waits for the full-stack before going to sleep;
end if

The pseudo-code 1 summarizes the CTM-based RSA. In accordance with this approach, the source node should receive a reply from all the potential relays so as to choose the next relay greedily – to select the closest node to the destination if there is one available.

C. *Auction-based RSA with Location Awareness*

The auction-based RS mechanism with location awareness makes use of Dutch auctions as an effective alternative to address the RS process in combination with an RMA scheme [4]. By using the auction-based RS strategy, the relay candidates independently exploit the location awareness to ponder their decision in taking part in the game or not.

The auction-based RS strategy starts when a given node has a packet to forward to the sink. The source node corresponds to the auctioneer. Then, the source node computes the forwarding regions so as to separate potential relays in time by giving them distinct priorities to bid based solely on their dwelling area (see figure 3). In the auction game relay candidates correspond to the bidders. Afterwards, the source node initiate the RTS/CTS handshake.

The RTS signaling packet encloses the forwarding regions that are transmitted to the potential relays as the asking price – initial hint. The relays that are available to undergo the current transaction divide themselves independently and autonomously through the forwarding regions and then reply to the source request with CTS packets according to the priorities of their dwelling areas. The priority of each region is determined based on the advance that a node may provide towards the destination: nodes located in the area closest to the destination have the highest priority to make their bids.

If there is more than one potential relay in a certain forwarding region, a collision will certainly occur. To deal with this situation two approaches may be employed effectively: either any simple splitting tree collision resolution algorithm is used [7], [9] or, preferably, a recursive and iterative auction-based strategy is utilized.

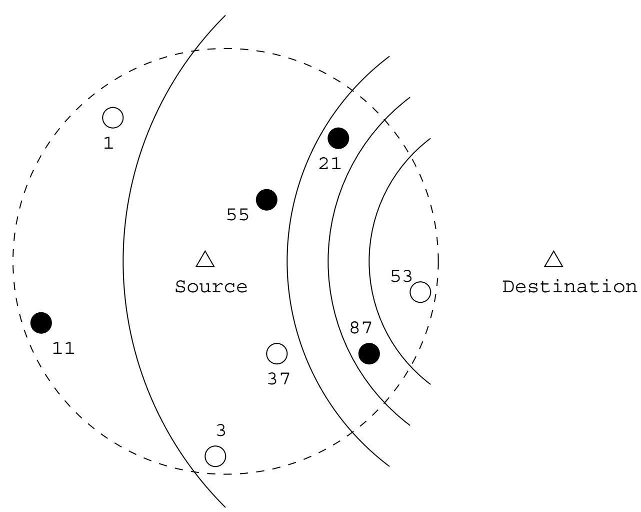

Fig. 3. Illustration of the auction-based RSA. Definition of forwarding regions. Relay candidates are identified by filled-circles. The dashed circle delimits the source's radio range.

Algorithm 2 Pseudo-code for the auction-based RSA.

```
Require: source's radio range, source position,
    destination position, potential relays positions.
Source Node computes the "bidding" areas based
    on the pre-defined number of forwarding regions
    (equivalent to the stack levels);
Source Node initiates RTS/CTS handshake;
for all Neighbor nodes (potential relays) do
  if Node can propagate packet then
    Relay locates itself in a certain forwarding
      region;
    Relay makes bid according to its priority;
  end if
end for
if There is collision then
  Source Node re-divides the colliding forwarding
    area only;
  for all Neighbor nodes (potential relays) do
    if Node resides in the colliding area then
      Relay locates itself in a certain forwarding
        region;
      Relay makes bid according to its priority;
    else {Node did not reply in the previous bid
      slot}
      Relay drops out of the ongoing transaction;
    end if
  end for
else if There is one relay only then
  Source Node forwards the packet;
else if There is no reply then
  Source Node waits for the full-stack before going
    to sleep (there is no relay around) and reset the
    connection;
end if
```

When the recursive auction-based strategy is employed, the source node recomputes the forwarding regions if a collision is detected. However, since the source node uses the location information in a sequentially increased way, only the colliding region is addressed. The nodes that are entangled in the current collision (and corresponding forwarding region) are indirectly identified by addressing the time slot in which the collision occurred. Equally important, potential relays that have not replied in the previous slot but detected the collision just drop out of the ongoing transaction. After recomputing the new forwarding regions, the source propagates an RTS packet and a new auction round starts.

Figure 3 illustrates the computation of the forwarding regions. For the first auction round, the relay candidates are divided into three groups, $\{[21, 87], 55, 11\}$. Since nodes $\{[21, 87]\}$ reply at the same time slot, a collision occurs. The source node then detects a collision in the first slot and recompute the forwarding regions accordingly. Nodes $\{55, 11\}$ also detect the collision and, as nodes of higher priority have already replied, drop out. Afterwards, potential relays in the first colliding area are reordered in the sequence $\{[], 87, 21\}$. Finally, after the first idle slot, node 87 replies and the auction stops.

Unlike a pure greedy approach, the recursive auction-based strategy may not provide an actual advance toward the destination. Differently, the auction-based solution may direct the packet back so as to find an alternative route if no suitable relay is found either due to topological holes or network dynamics (node's duty cycle). In the auction-based approach, the virtual stack-levels are mapped into the forwarding areas. The forwarding areas are made equal in order to set equal probability of finding a relay towards the destination. And yet different priorities for replying are determined based on the advancement each forwarding area may provide towards the destination.

The proposed auction-based RS strategy is summarized in the pseudo-code 2.

III. Simulation Framework

In this section, we describe the framework used to assess the performance of the proposed relay selection mechanism. In particular, a review of the cluster-based geographic routing protocol proposed in [2] is given, followed by a description of simulation environmental parameters such as the network topology, traffic generation mechanism and node deployment model, which is given in the subsequent subsection.

A. Cluster-based Routing Protocol

The position-centric routing protocol is composed of two operational parts: global routing among clusters and localized RS inside clusters. The former, which was introduced in [2], exploits network graph spectral analysis to divide network into clusters composed of sufficiently connected nodes; while the latter deals with localized RSA inside clusters.

The cluster-based routing protocol to be described shortly is designed under the following assumptions. During a discovery procedure (which is not discussed in this contribution), each node discovers its neighbors and forwards the connectivity information to a central processing unit, based on which the connectivity matrix of the network is built. The central unit then clusterizes the network and assigns an identification (ID) number to each cluster and computes their geographical location. For short, the location of the geographical center of a cluster will hereafter be referred to as the cluster location.

The clusterization method relies on the graph-theoretical spectra analysis of the network graph. Specifically, clusters are identified by evaluating the eigenvalues and eigenvector components of the Laplacian matrix associated to the meshed network graph [10]. The method progressively decomposes the overall network into sub-clusters using as stop criteria either the minimum completeness or the compound number of nodes. For details please refer to [11].

Notice that a real coordinate system is not strictly necessary. In fact, methods that do not relay on actual location to route packets may be exploited to build a virtual coordinate system that can be used as input to the cluster-based routing [12], [13].

Each node is then informed of which cluster it belongs to and the IDs and geographical locations of adjacent clusters (this is a reasonable assumption since the central unit has acquired knowledge on the shortest path to all nodes after network discovery) [2].

B. Simulation Environment

The joint MAC relay selection mechanism and the cluster-based routing protocol is assessed via computer simulations. A dynamic radio network simulator is used to evaluate the overall network performance and effectiveness of the proposed solutions. The system-level simulator was implemented using C++ Object Oriented Programming (OOP) language and following event-driven paradigm.

All simulations were performed using topologies generated randomly, with nodes uniformly distributed over a 125m-wide square with a concave hole of shape resembling "Packman" placed in the middle (see Figure 6). The minimum node degree and corresponding radio range are set so as to guarantee the connectivity of the network [14], considering a connectivity probability of at least 99%.

All nodes operate independently and traffic is Poisson-distributed, with adjustable packet inter-arrival time $\lambda = 0.5$pkt/s, assigned randomly to the nodes. The nodes' buffers are considered long enough to avoid packets to be discarded due to overflow. The time a packet stays queued in a node's packet buffer, including the time the node sleeps, is added to the final delivery latency metric.

Detailed radio propagation models are not considered in this work. Instead a simplified two-state (busy, idle) channel model is used to emulate the air interface occupancy during packet transmissions. Nodes only transmit when the channel is idle.

It is assumed in the simulation set-up that network discovery had been already performed and that the network is in a steady-state regime of operation, when the routing protocol itself starts to operate. An underlying assumption is that the network discovery was coordinated (or at least overlooked) by the central unit which, in the process, acquired the entire network connectivity matrix.

At the beginning of each simulation, a sink is chosen amongst the nodes around the coordinates $X =$ 125m, $Y =$ 62.5m, such that it is diametrally opposite to the concave portion of the hole (see figure 6). This configuration accounts for a worst-case scenario, in the sense that the number of nodes subject to dead-end problems is maximized.

Key simulation parameters are listed in Table I. Some of the figures were taken from [15].

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Area	Square (125 m)
Radio range	18.37 m
Duty Cycle	10%
Backoff Interval	0.219s
Awake Interval	0.016s
Transmission Time Interval	0.0521s
Cluster Size	15 Nodes
Number of Nodes	215 Nodes
Packet inter-arrival rate	0.5 packets/s
Number of stack levels	3 levels
Number of forwarding regions	3 regions

IV. SIMULATION RESULTS

The performance of the auction-based RSA is evaluated in terms of the distribution of the number of iterations required in order to select the node to which a packet must be forwarded, under a greedy geographical criterion. The results for the cluster-based geographic routing are presented in terms of the Cumulative Distribution Function (CDF) of the PDSR as a function of the corresponding Average Packet Delivery Latency (APDL), and in terms of the distribution of route path length (in number of hops). A routing trajectory obtained during systemic simulations is also shown for illustration. In order to ensure the statistical significance of the results, each simulation lasts the time necessary for the sink to collect 5000 packets.

Figure 4 shows the distribution of iterations required in order to select a relay, which corresponds to the Contention Resolution Interval (CRI), when using the CTM-based RSA. For the generation of this figure, we have considered a virtual stack with three levels. The priority to reply is determined randomly (there is no side-information) based on the probabilities derived from the number of levels of the virtual stack. Consequently, the number of iterations to resolve the contention may vary significantly and the CRI may linger too long before the relay is determined. Moreover, the contention resolution may incur in several collisions even for few relay candidates. This fact happens because the relay candidates have no side-information to ponder their decision whether to take part in the contention or not. Additionally, the source can only select the most appropriate candidate after all potential relays have already replied (in terms of the separation distance to the destination).

Figure 5 shows the distribution of the required number of contention resolution iterations when using the auction-based RSA.

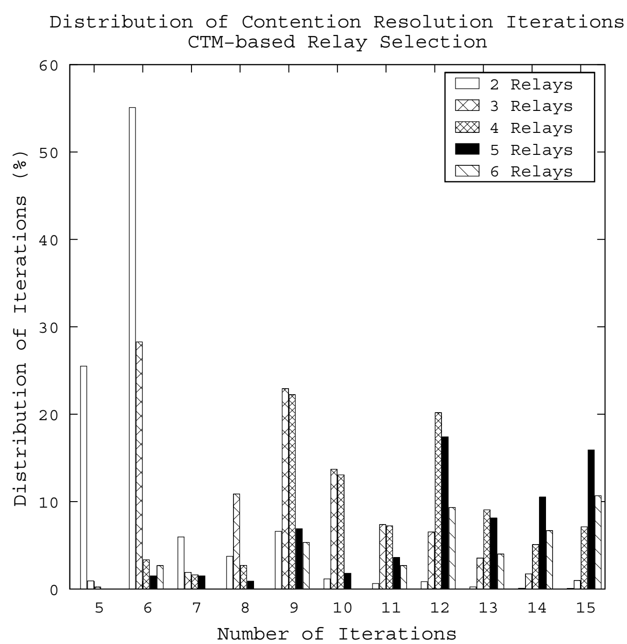

Fig. 4. Distribution of iterations required to resolve the contention for increasing number of relay candidates. CTM-based CRA with 3 stack levels

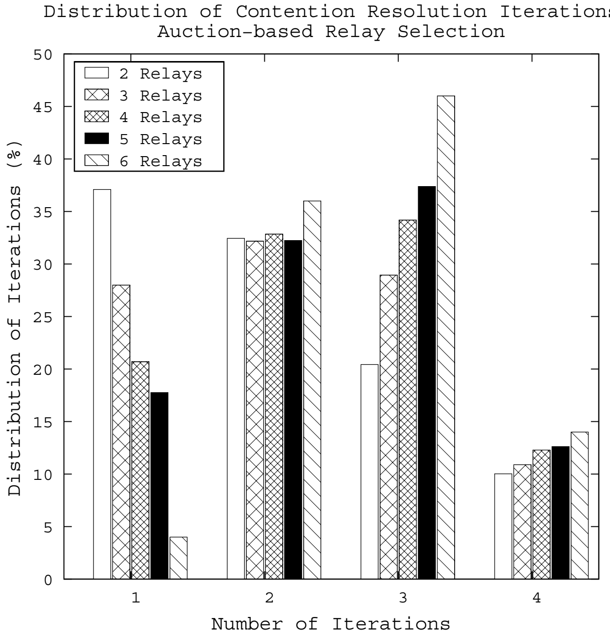

Fig. 5. Distribution of iterations required to resolve the contention for increasing number of relay candidates. Auction-based RSA with 3 forwarding regions

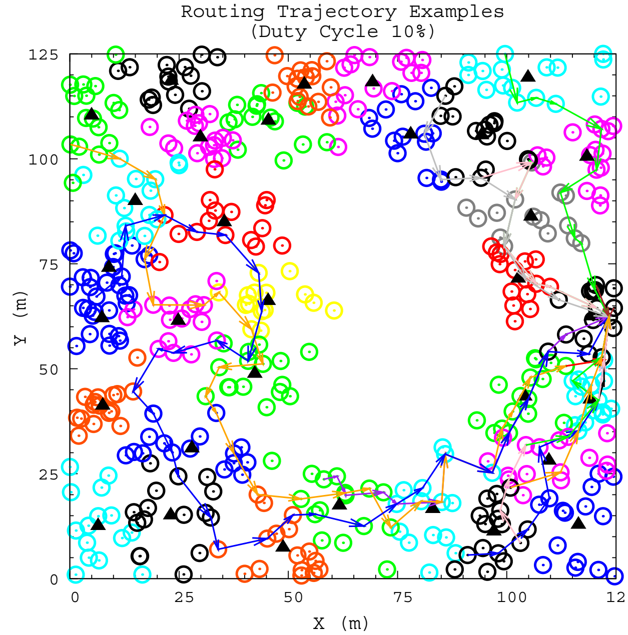

Fig. 6. Illustrative trajectories using the cluster-based routing (minimum cluster size equal to 15).

In contrast to the solely random CTM-based RSA, the auction-based solution makes use of location awareness in order to influence the replying priority of potential relays.

The source node starts the auction round by providing the initial hint (asking-price), and thereafter each of the potential relays locates itself independently and autonomously in one of the forwarding regions. Afterwards, they reply to the source request sequentially based on the priority of their own forwarding region. When the very first CTS message is received by the source, the contention is resolved and the packet is forwarded.

Therefore, by using the location information, a suitable relay is selected quite fast. For the simulated scenarios, the CRI is restricted to four iterations at most. Notice that not only the CRI is maintained small, but also the relay that is selected out of the original set of the available relay candidates is the most appropriate[3].

The benefit of using the auction-based RSA increases for higher number of relay candidates. For example, it can be seen from figure 5 that a contention may be resolved at a single iteration with 5% probability, even if as many as six relay candidates are present.

Figure 6 exemplifies the trajectories around the concave hole when the cluster-based geographic routing is used in conjunction with the auction-based RSA. Notice that the simulation scenario presents a harsh network topology. It is remarkable that even in this extreme configuration nodes located at the concave portion of the hole (Packman's mouth) are still able to propagate packets towards the final destination, albeit at the expense of a higher APDL, due to the longer trajectories circumscribing the hole [2].

[3]If there is no suitable relay towards the sink the packet may temporarily fall back so as to find an alternative trajectory.

Figure 7 shows the PDSR for increasing values of APDL (transmission latency). Both scheduled and auction-based RSAs are evaluated. Notice that the scheduled RSAs is an idealized strategy and is used so as to sort out the effectiveness of the proposed game-theoretical approach.

It is found that the auction-based RSA retains a substantial portion of the PDSR associated with a system employing the perfect scheduled RSA. In fact, the auction-based strategy may allow packets to fall back for a while so as to find alternative routes towards the destination only if there is no relay on the way to the destination. In turn, the proposed RSA proves to be resilient enough to absorb the variable network topology and to continue delivering packets to the destination, albeit at the expense of a higher APDL, due to the longer trajectories circumscribing the hole.

We observed a trade-off between restart the connection – the auctioneer does not have to necessarily accept the bids – and redirect the packet, though we did not address this problem in this contribution specifically. Indeed, the auction-based performance loss in terms of PDSR, when compared to the ideal case, is due to the deviations that may occur from the shortest trajectory towards the destination, since a packet is discarded when the intermediate destination swept all adjacent clusters without finding any suitable relay characterizing a loop [2].

Figure 8 shows the distributions of the number of hops – in excess of what would take if packets were to be forwarded in a straight-line, with zero awaiting time (perfect relaying) – required by the routing protocols under the simulated conditions. When compared to the scheduled RSA, the auction-based alternative may presents longer trajectories, because the proposed game-theoretical approach may allow relay candidates that are further from the destination than the source to be selected as relay so as to find alternative route.

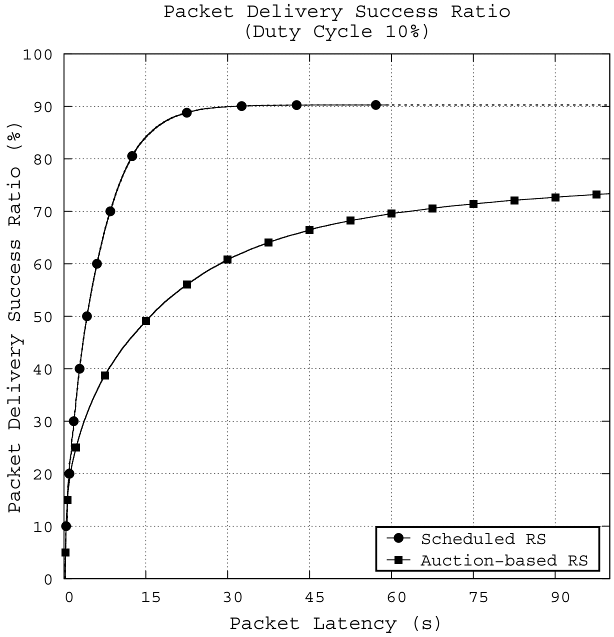

Fig. 7. Packet delivery success ration with duty cycle of 10%.

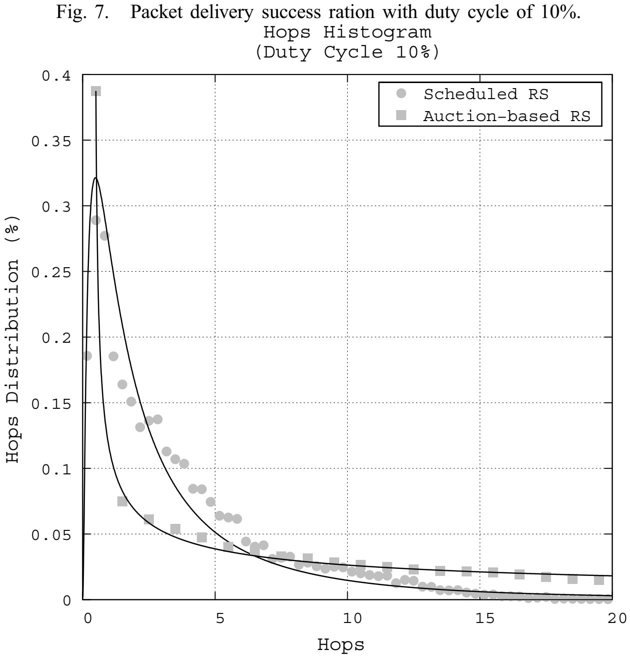

Fig. 8. Distribution of excess-hop with duty cycle of 10%.

Another aspect that may influence the auction-based RSA to eventually generate longer trajectories is that all nodes dwelling the same forwarding region have the same priority to reply despite different angular deviations they may provide. Indeed, a natural improvement for the current implementation resort to the joint evaluation of both distance and angle in order to drive the decision and consequently reduce the deviation from the desirable trajectory towards the destination.

V. Conclusions

This contribution proposes the utilization of Dutch auctions as an effective alternative to address the RS process in conjunction with an RA-MAC solution.

When compared to well-known splitting tree CRAs for Random Access Systems (RASs), the auction-based RSA is an interesting alternative to select a suitable relay in a short CRI with sequentially increasing use of location awareness. Therefore, the proposed solution is an appropriate strategy to perform simultaneous channel access and relay selection in such multi-hop WSNs. Furthermore, successive rounds of Dutch auctions may be effectively employed to deal with contention avoidance and contention resolution stages of the non-cooperative games between source and relay nodes. It has been observed that the auction-based RSA allows autonomous behavior between bidders while demanding little redundancy among them. The intertwined auction-based MAC and network routing solution retains a substantial portion of the PDSR associated with a system with perfect relay selection.

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