Multiratecast in Wireless Fault Tolerant Sensor and Actuator Networks*

Xuehong Liu[1], Arnaud Casteigts[1], Nishith Goel[2], Amiya Nayak[1], and Ivan Stojmenović[1]

[1] School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada
[2] Cistel Technology Inc., Ottawa, ON, Canada

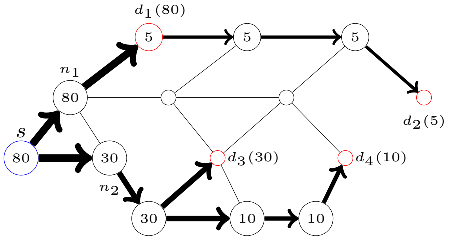
***Abstract*—We study the multicast problem in wireless sensor networks, where the source can send data to a fixed number of destinations (actuators) at a different rate (*multiratecast*). A typical motivation of such communication scheme is to enable fault tolerant monitoring applications where data is reported to more than one actuators using different rates that decrease with the sensors distance, so that if the closest actuator fails, others can take over from it. We propose two multiratecast routing protocols: *Maximum Rate Multicast (MRM)* and *Optimal Rate Cost Multicast (ORCM)*, which are the first localized position-based protocols specifically designed for this problem. The first, MRM, selects the next forwarding neighbor(s) in order to favor destinations requiring the highest rates, while the second, ORCM, evaluates several possible choices and select the best according to a *cost over progress* ratio criterion. The two protocols are compared by simulation, using a new metric that takes the rate into account when computing a multicast cost. Results show that ORCM provides a better routing performance in case of a small number of destinations, while MRM performs better for large numbers of destinations and has a lower computational cost. MRM also behaves better than ORCM when the variance among the rates becomes important.**

I. INTRODUCTION

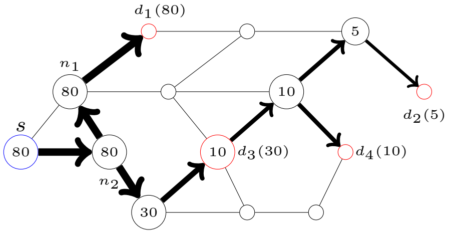
A wireless sensor network (WSN) is a network consisting of spatially distributed sensing devices, whose purpose is to monitor a given object, surface, or volume in a cooperative fashion, using wireless communication capabilities. Their application domains are various, from military battlefield to civil area with problems such as pollution monitoring, intrusion detection and tracking, traffic control, *etc.* In a WSN, each sensor device composing the network, called *node*, can directly communicate with the devices that are within its radio range, or *neighbors* (assuming these nodes have the same range). Non-neighbor nodes can also communicate indirectly by using the nodes between them as *relays*. In this case the communication is said *multi-hop* and it involves the use of a *routing* protocol to decide what relay nodes should be used. When such communication happens between a *source* and a single *destination*, we talk about *unicast*. If several destinations are considered, then we talk about *multicast*, and if all nodes are destination, *broadcast*.

Typical use of WSN include sensor nodes monitoring a given area and reporting the sensed data to a sink or *actuator* that are capable of applying subsequent actions (*e.g.* alarm triggering). When the monitoring area is large and critical, such as with intrusion detection or object tracking in a battle region, then several actuators might be deployed. In this case, the region can be subdivided into smaller areas, with each actuator in charge of collecting data from overlapping subsets of areas. Typically, the rate could be inversely proportional to the distance, so that if the closest actuator of an area is damaged, another one can take over without loosing all the historical information of the place.

We focus in this paper on the design of *rate-based* multicast, or *multiratecast*, routing protocols to support such applications. We first introduce a new metric to calculate the cost of rate-aware multicast paths. Indeed, the usual *hop count* and *retransmission number* metrics do not reflect the real efficiency of a path in this context. This idea is illustrated on Figure 1, where two different paths are proposed to serve a given set of destinations (with given rate requirements). Here the 'shorter' path in terms of both metrics is actually the most expensive if we consider the number of messages to be effectively sent, that is the *cumulative rate* of retransmissions.



(a) Path A - 9 retransmissions, 11 hops, total rate cost: 255



(b) Path B - 7 retransmissions, 9 hops, total rate cost: 295

Fig. 1. Impact of the rate on a multicast path cost. Four destinations (d_1, d_2, d_3, and d_4) are considered, each one having a different required rate (between parenthesis). Numbers in circles indicate the retransmission rate.

The design of WSN multicast protocols is challenging. Sensor devices have small processing power, limited buffer size, radio bandwidth, and especially limited battery capacity. Regarding the energy consumption, the networking activity is far more critical than the computational or sensing activities. Routing protocols thus need to minimize this aspect in priority. If the network is potentially large or subject to reconfigurations (due to node failure or mobility for example), then protocols relying on a global overlay structure maintenance turn out very costly in overhead, and protocols that use only local information such as position-based (or *geographic*) routing protocols are preferred.

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We propose two geographic multicast protocols that take into account potentially different rate for destinations. They also consider the so-called *wireless advantage* (which consist in assuming that what is sent to a neighbor is also received by the other neighbors). These protocols are localized and use only node position information to make routing decision. To the best of our knowledge, no existing protocol fulfills these requirements. Article [12] tackled the multiple rate problem, but proposed a non-localized protocol that requires a global tree structure to be built. Additionally, the construction of the tree is guided by independent costs for edges, which does not consider the wireless advantage.

The protocols we propose here are both adaptations of the *Greedy Face Greedy* principle [1], which basically consists in alternating greedy progression toward destinations (when advance is possible), and face recovery when a local optimum is found (to find a node from which greedy can be resumed). Both protocols differ only on their greedy mode, and more precisely on the method they use to select the next forwarding nodes at each hop. The first protocol, *Maximum Rate Multicast* (MRM), choose them linearly by prioritizing the more demanding destinations, while the second, *Optimal Rate Cost Multicast* (ORCM), evaluates different possible routing choices by combining distance progression and rate considerations (thereby implementing the more general concept of *best cost over progress ratio* [5]). Three candidate ratio formulas are proposed and compared in the paper. Regarding the possible routing choices evaluated, ORCM evaluates all possible choices if the number of destination is considered as *small*, and a subset of them if it considered as *large*.

One limitation of the proposed protocols lies in the same aspect that makes them attracting: they are position-based protocols, which means they assume a *location service* to inform them about destinations positions. In the same class of assumptions, they assume that nodes are aware of their own positions (either using *GPS*-like receptors, or virtual coordinates [2]), and of the positions of their neighbors (using any type of beaconing scheme). The two multiratecast protocol proposed in this paper are studied and compared by simulation. The results mainly show that ORCM provides slightly more efficiency than MRM when it performs a complete evaluation (small number of destinations), and a lower efficiency otherwise. MRM appears better in average, and has the advantage of a very low computational cost. The paper is organized as follows: in Section II, we describe and discuss the most related protocols found in the literature. Section III introduces in detail the two proposed protocols, and discuss some metric-related topics. Then Section IV proposes a summary of the simulation results and Section V eventually concludes.

II. LITERATURE REVIEW

An important amount of routing protocols has been developed the past few years for wireless sensor networks. These protocols can be roughly divided into unicast (one-to-one), multicast (one-to-several), and broadcast (one-to-all) protocols. Due to the natural limitations of sensor networks, the broadcast scheme should be avoided as much as possible, especially in large networks. This section presents a short selection of unicast and multicast geographical protocols, some of which have directly influenced the design of those we are proposing in this paper.

A. Geographical unicast in WSN

Geographical routing protocols rely on the assumption that nodes can determine their own location and acquire as needed the location of a message destination. Based on this information, the routing process can be performed without any global route discovery and using only local information at every hop. This feature drastically reduce network resource consumption and enable a low-cost adaptation after topological changes. *Greedy-Face-Greedy (GFG)* [1] is such a localized protocols whose principle consists in alternating two routing modes: *greedy routing*, where a greedy progression is performed toward the destination (if feasible), and *face routing*, to recover from a situation where no advance is possible. More precisely, in greedy mode, the current forwarding node selects, among its neighbors, the node which is the closest to the destination. Then it includes this information in the packet, and sends it. Upon receiving a packet, the selected neighbor identifies itself using the information and repeats the same operations. This greedy process iterates until a *local optimum* is reached (*i.e.,* no direct neighbor is closer to the destination), then *face routing* is engaged to find a node that is closer to the destination than this local optimum, at which point greedy forwarding is resumed. Packet routing in face routing mode consists in driving the packet along the face that was reached at the local optimum (in a chosen direction). Such process can be done locally and without additional overhead by considering the *Gabriel Graph* (a planar subset of the network). When the current node is closer than the last local optimum, greedy mode is resumed from it. The two modes alternate until the destination is reached (delivery is guaranteed in networks that remain static during the process).

B. Geographical multicast in WSN

Various geographical multicast protocols have been proposed so far [3, 4, 6, 7, 11, 13, 14]. However, among them, only GMP [13], PBM [6], and GMR [11], do not rely on global structures or broadcast control messages. GMP is a localized protocol that tries to build a *virtual* multicast *Steiner tree* as follows: at each hope, the current node finds among its destinations the pair having the shortest relative distance, it creates a virtual destination to represent the pair, and start anew until all destinations are represented by a single virtual node, toward which greedy forwarding is performed. Once at this position, the path is split and the process is repeated in each direction. The main problem is that merging the destinations by pair may end up in wrong position estimations, and routes in the opposite direction of some destinations.

The protocol PBM is a generalization of the Greedy-Face-Greedy principle to multicast contexts. When a forwarding node cannot find any neighbor providing advance toward some of the destinations (*i.e.,* a *local optimum* is reached), face routing is engaged for those destinations until the underlying node becomes closer to one (or several) of them, then greedy mode is resumed those destinations, and face routing continues for the others. To select the forwarding neighbors in greedy mode, PBM relies on a trade-off between individual shortest paths for each destination and overall cost minimization, according to a chosen balance parameter λ. More precisely, in each step, the underlying node evaluates all possible combinations of next forwarding neighbors (to assign to each a disjoint subset of destinations), and select the best ranked choice. The main problems with this approach is that determining the optimal value for λ is not a trivial task, and the evaluation complexity increase exponentially with the number of destinations.

GMR is another localized multicast protocol that extends the Greedy-Face-Greedy principle. Contrarily to PBM, which generates and evaluates all choice possibilities, GMR considers only a subset of them. First, it determines the closest neighbor to each individual destination, then groups together the destinations for which the closest neighbor is the same. This process leads to a *partitioning* (set of destination subsets) $P = \{M_1, M_2, \ldots, M_i, \ldots, M_m\}$, called the *initial partitioning*. Once built this partitioning, GMR merges iteratively some of the subsets with the aim to minimize the overall *cost over progress ratio* of the partitioning, where *cost* is the number of neighbors selected, and *progress* is the sum of all individual distance advances toward destinations. This merge process is detailed by Algorithm 1. The main advantage of GMR over PBM is that it does not need any input parameter (such as the balance value λ) and its complexity does not explode with the number of destinations, thanks to its merge process.

Algorithm 1 Merge process for partitionings

```
input: Initial partitioning $P = \{M_1, M_2, \ldots, M_k\}$
output: Optimized partitioning $P' = \{M'_1, M'_2, \ldots, M'_{k'}\}$
repeat
  $bestReduction = 0$
  for all possible pairs $\{M_i, M_j\}$ in $P$, do
    build a partition $P_{tmp}$ from $P$ by merging $M_i$ and $M_j$
    $reduction = cost(P)$-$cost(P_{tmp})$
    if $reduction > bestReduction$ then
      $bestReduction := reduction$
      $P_{next} := P_{tmp}$
    end if
  end do
  if $bestReduction > 0$ then $P := P_{next}$
  else return $P$ // program end
  end if
end repeat
```

C. Multirate multicast in WSN

The routing protocols previously discussed have been designed for single rate scenarios, that is, they consider data transfers at a same rate toward all destinations. Regarding rate aspects, a rate-adaptive multicast protocol has been proposed for mobile ad hoc networks in [8]. This protocol adapts the rate of communication to the quality of the links in order to reduce the overall networking consumption. However, it does not consider the rate as a required parameter, and is therefore not relevant for the problem we are considering. At the best of our knowledge, the only work that tackled this problem is in [12]. This protocol builds a rate-aware multicast tree by flooding $Explore$ messages from the source to the destinations. Once reached, the destinations send back Ack messages containing their required rates, which build the multicast path on their way back to the source. Some localized techniques are used during this process to optimize the tree. However, the very fact that the protocol use broadcast and build a global overlay structure makes it costly and vulnerable to topological changes.

III. THE PROPOSED MULTIRATECAST PROTOCOLS

In this section, we introduce two novel multicast protocols, which both are purely localized and apply a Greedy-Face-Greedy strategy to guarantee delivery to destinations. These protocols can be used in both static and partially-dynamic sensor networks, and they take into account the different rates of destinations while taking routing decisions. Obviously, these protocols do not generate optimal multiratecast routing paths (which is an NP-complete problem, as generalizing the optimal multicast tree problem in wireless networks, proved NP-complete in [10]). They provide however important benefits over the existing unicast and multicast solutions.

A. Preamble

a) Network assumptions: the two proposed *multiratecast* protocols are geographical (position-based) and localized. We assume that the nodes know their own position (through a positioning service like *GPS*), their neighbors positions (using any beaconing scheme), and that any source can obtain the positions of its destinations (thanks to a location service). Regarding communications, we assume ideal MAC and PHY layers without loss, and that each node is individually capable of forwarding data at the maximum rate among destinations. The routing choices are solely done by looking at local neighbor positions with respect to destination positions, there is no routing table nor global overlay structure needed to be built. Finally, the network topology can change between two consecutive routing tasks without other cost than updating the new positions of destinations on the sources, if changed.

b) Rate cost metric: as stated in the introduction, the *hop count* and *transmission number* metrics do not correctly reflect the efficiency of a multi-rate multicast path, as the transmission rate can differ from one relay node to another. Therefore, in order to measure this efficiency, we decided to use the sum of the (output) rates at each relay node, which is proportional to the number of message to be sent. More formally, given a set of relay nodes $R=\{r_1,r_2,\ldots r_{|R|}\}$ composing a multicast path, we define the path cost as $\sum_{i=1}^{|R|} rate(r_i)$.

c) Overview of the protocols: both protocols, *Maximum Rate Multicast protocol* (MRM) and *Optimal Rate Cost Multicast* (ORCM), apply the multicast extension of Greedy-Face-Greedy described in Section II-B, and differ only on their greedy mode strategy. As a recall, the greedy mode is as follows. At each forwarding node, a set of next forwarding nodes is selected, each one being given the responsibility to repeat the process with a subset of destinations, until those destinations are reached. In order to apply such a routing, the messages must contain, in addition to the data, a header including the source node position, the current node position, the rate at which the data is currently sent by the current node, and the list of association between next forwarding node and corresponding subsets of destinations. The core problem is now to decide how these forwarding nodes should be chosen to minimize the overall routing cost.

B. The Maximum Rate Multicast protocol (MRM)

The basic idea behind MRM is to give priority to destinations that have the highest required rate. More precisely, at each step, the current node tries to find the neighbor node that is closest to the destination requiring the highest rate. Then it assigns to this neighbor all the destinations for which it would provide any progression (the message is not yet sent at this point). The current node iteratively repeats the process with remaining destinations until all of them are assigned, then sends the message. This process is described by Algorithm 2.

Algorithm 2 MRM high-level algorithm

```
input: destination greedy list $D_L$, neighbor list $N_L$
output: list of couples (neighbor,destination) $C_L$
create an empty couple list $C_L$
while $D_L$ is non empty, repeat
  $d_{max} := \emptyset$
  for each destination $d$ in $D_L$, do
    if $rate(d) > rate(d_{max})$, then
      $d_{max} := d$
  $n_{max} := +\infty$
  for each neighbor $n$ in $N_L$, do
    if $distance(n, d_{max}) < distance(n_{max}, d_{max})$, then
      $n_{max} := n$
  for each destination $d$ in $D_L$, do
    if $distance(n_{max}, d) > distance(c, d)$, then
      append $(n_{max}, d)$ to $C_L$
      remove $d$ from $D_L$
```

C. The Optimal Rate Cost Multicast protocol (ORCM)

The basic idea behind ORCM is to evaluate different routing choices and select the one having the best *cost over progress ratio* where, contrarily to the existing protocols presented in Section II, the *cost* takes into account the related rates values. In order to maintain a reasonable calculation complexity, ORCM adapts its high-level strategy to the number of destinations. If this number is small (under a given threshold), then it applies the same strategy as PBM by generating and evaluating all possible combinations of destinations partitionings (for affectation of destinations subsets to local neighbors). If the number is large (above the threshold), it applies the strategy of GMR by computing a first initial partitioning and iterating a merge process to optimize it (see Algo. 1). The threshold value basically depends on the computation power of sensor nodes, we considered it at 6 in our simulations.

d) Illustrative example: let us consider the situation described on Figure 2, where a current node c wants to select the next forwarding nodes toward d_1, d_2, d_3, and d_4 (each having possibly different rate requirements).

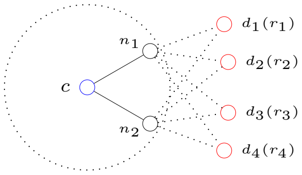


Fig. 2. Example of basic routing scenario

If 4 is considered as a *small* number of destinations, then all the possible partitionings are generated, which leads to the 14 following sets of destinations subsets:

$$\begin{array}{ll}
P_1 = \{\{d_1, d_2, d_3, d_4\}\} & P_8 \ = \{\{d_1, d_4\}, \{d_2, d_3\}\} \\
P_2 = \{\{d_1\}, \{d_2, d_3, d_4\}\} & P_9 \ = \{\{d_1\}, \{d_2\}, \{d_3, d_4\}\} \\
P_3 = \{\{d_2\}, \{d_1, d_3, d_4\}\} & P_{10} = \{\{d_1\}, \{d_3\}, \{d_2, d_4\}\} \\
P_4 = \{\{d_3\}, \{d_1, d_2, d_4\}\} & P_{11} = \{\{d_2\}, \{d_3\}, \{d_1, d_4\}\} \\
P_5 = \{\{d_4\}, \{d_1, d_2, d_3\}\} & P_{12} = \{\{d_2\}, \{d_4\}, \{d_1, d_3\}\} \\
P_6 = \{\{d_1, d_2\}, \{d_3, d_4\}\} & P_{13} = \{\{d_3\}, \{d_4\}, \{d_1, d_2\}\} \\
P_7 = \{\{d_1, d_3\}, \{d_2, d_4\}\} & P_{14} = \{\{d_1\}, \{d_2\}, \{d_3\}, \{d_4\}\}
\end{array}$$

These partitionings are then all evaluated, and the best is chosen. Now, if 4 is considered as a *large* number of destinations, then the *initial partitioning* is generated (*i.e.,* destinations grouped by common closest neighbor), which leads to $P' = \{\{d_1, d_2\}, \{d_3, d_4\}\}$, where n_1 serves $\{d_1, d_2\}$ and n_2 serves $\{d_3, d_4\}$. According to the merge process, the two subsets in P' are eventually merged into $P'' = \{\{d_1, d_2, d_3, d_4\}\}$ if it offers a better cost over progress ratio than P'.

1) Cost over progress ratio calculation: we propose three methods for calculating the cost over progress ratio of a given partitioning, each one considering a different aspect. Below is a set of notations used to simplify the corresponding formulas.

- given a set of destination $D = \{d_1, d_2, \ldots, d_{|D|}\}$, $rate(D) = max(rate(d) : d \in D)$
- given a current node c, one of its neighbors n, and a destination d, we pose $prog(c, n, d) = dist(c, d) - dist(n, d)$, the progression that n offers from c to d.
- given a current node c, one of its neighbors n, and a set of destinations $D = \{d_1, d_2, \ldots, d_{|D|}\}$, we pose $prog(c, n, D) = \sum_{i=1}^{|D|} prog(c, n, d_i)$, the *cumulative* progress that n offers from c toward a group of destinations.
- finally, we note $N(c)$ the set of neighbors of a node c.

a) ORCM_A (set cost focus on subset): ORCM_A defines the cost of a partitioning as the sum of the individual and independent costs of all its subsets. The cost of each subset is the ratio of its rate (highest rate among destinations in this subset) over the best cumulated distance progress achievable by a same neighbor for this subset. More formally,

$$ratio(M) = \frac{rate(M)}{max(prog(c,n,M) : n \in N(c))}$$

Once the cost of each subset is calculated, the global cost of the partitioning $P = \{M_1, M_2, \ldots, M_{|P|}\}$ is defined as their sum

$$ratio(P) = \sum_{i=1}^{|P|} ratio(M_i)$$

b) ORCM_B (set cost focus on individual destination): ORCM_B also defines the cost of a partitioning as the sum of all its subset costs. Here however, the cost of each subset is defined as the sum of costs of individual destinations (with respect to the maximal rate in the subset and the best common forwarding neighbor). The intuitive idea behind this method is to give more importance to individual path optimization.

$$ratio(M) = min((\sum_{i=1}^{|M|} \frac{rate(M)}{prog(c,n,M)}) : n \in N(c))$$

c) ORCM_C (rate cost based on the whole destination set): contrarily to the two previous methods, ORCM_C focus on the destination set as a whole by defining the cost as the sum of all subset rates over the sum of all maximum subset distance progress. The intuitive idea behind this method is to chose, for each individual subset, the forwarding neighbor that will best profit the overall destination set. More formally,

$$ratio(P) = \frac{\sum_{i=1}^{|P|} rate(M_i)}{\sum_{i=1}^{|P|} max(prog(c,n,M_i) : n \in N(c))}$$

IV. PERFORMANCE EVALUATION

This section presents a comparison of the proposed protocols by means of numerical simulations. We studied their comparative efficiency in various networking context, by varying the *number of nodes* (from 100 to 1000), the *average degree* (from 8 to 32), the *number of destinations* (from 2 to 50) and the *rate distribution* among destinations (standard deviations from 0 to 200% of the average rate). As a recall, ORCM behaves differently for *small* and *large* numbers of destinations. Both modes were automatically switched (with the threshold at 6 destinations). Regarding the network topology, we generated 50 connected random unit graphs (*CRUG* [9]) for every scenario and ran on each of them the protocols MRM, ORCM_A, ORCM_B, and ORCM_C. Each result shown in this section is the 50 values average.

2) Simulation results:

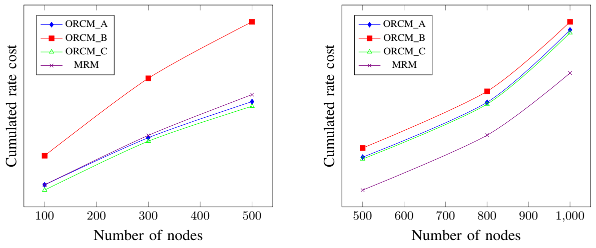
a) Impact of the Number of Nodes: for a same average degree, number of destinations, and rate distribution, we varied the number of nodes. The result, given on Figure 3, show that the routing cost increase sub-linearly with it, which is not surprising as increasing the number of nodes also increases (but more slowly) the average number of relay nodes between source and destinations. The difference between ORCM_B and the others, in case of *small* numbers of destinations (complete evaluation mode for ORCM), is more striking. Indeed, ORCM_B generates paths in average 50% more costly than the others (that have comparable performance with a slight advantage for ORCM_C). With *large* numbers of destinations (partial evaluation mode for ORCM), MRM performs better than ORCM, mainly due to the fact that the subset of partitionings evaluated by ORCM does not always include the best one. To state it clearly we compared the average performance of both ORCM modes for a same number of destinations (5 destinations) and observed an average difference of 20% between them (these results are available in the master thesis of the first author).

b) Impact of the Network Density: for a same number of destinations, rate distribution, and number of nodes, we varied the average degree of the nodes (that is, the density of the network). Simulation results, given Figure 4, show that the routing cost decrease dramatically as the average degree increases. This behavior has at least two explanations. First, since the network is denser, there is more chance for relay nodes to find ideally positioned neighbors with regard to destinations. Second, as the density increases, the probability to switch into *face routing* mode obviously decreases, thereby shortening the average path length. The comparative efficiency of the four protocols is similar to that of the previous test.

c) Impact of the Number of Destinations: for a same number of nodes, average degree, and rate distribution, we varied the number of destinations. Obviously, the routing cost increases with the increase of the number of destinations (as we plotted here the cumulated cost of the path). However, this increase is sub-linear, with a slope ratio of 0.8 for *small* number of destinations (Fig. 6(a), except for ORCM_B at 1.2), and 0.6 in average for *large* numbers of destinations (Fig. 6(b)). This basically means that the benefit of the path sharing increases with the number of destinations. Note that MRM still outperforms all ORCMs for *large* numbers of destinations.

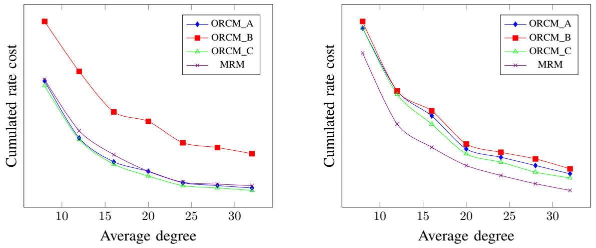
d) Impact of the Rate Distribution: for a same number of nodes, average degree, and number of destinations, we varied the distribution of rates among destinations (while keeping a same global average for them). The results, given Figure 5, show a similar comparative performance to what has been observed so far (ORCM_B being removed from the left two plots for scale purpose). It can be noticed however that MRM reacts slightly better than ORCMs to the growth of the deviation (even if its absolute performance is comparatively lower for *small* numbers of destinations). We also observe that as the standard deviation becomes high, all the routing protocols tends to have a similar performance (especially for *large* destination numbers). Indeed, as the deviation increases, the required rate of some destinations becomes large in comparison to others, and consequently the multicast cost becomes closer to the sum of unicast paths toward these destinations.

e) Multiratecast v.s. *sum of unicast:* to study the *absolute* efficiency of the multiratecast protocols, we compared our simulation results to the corresponding sums of unicast costs (considering the same rate-based metric). The reason why we compared them with *unicast* rather than with *non-rate-aware multicast* protocols is that we expect the first to perform better than the second in the case where different rates are required (the second would use the maximal rate at each relay node). The unicast routing protocol we take as a reference is the *Greedy-Face-Greedy* protocol. Regarding the multiratecast protocol, we have chosen MRM because it offers the best average efficiency (with respect to both *small* and *large* numbers of destinations). Figure 7 shows the comparison results in various contexts. Fig. 7(a) shows variation of the rate distribution among destinations. Obviously, the unicast is not affected, whereas MRM is and its cost converges toward the unicast cost (for the same reason as previously discussed).



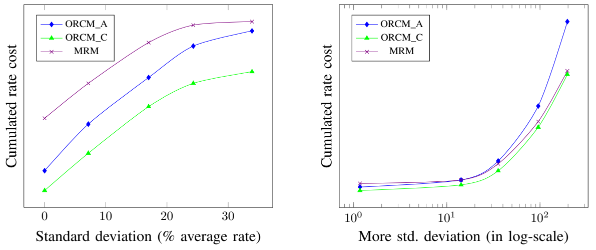
(a) 5 destinations (b) 10 destinations

Fig. 3. Variation of the number of nodes

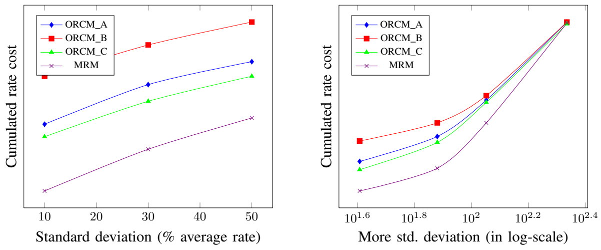


(a) 5 destinations (b) 30 destinations

Fig. 4. Variation of the average degree

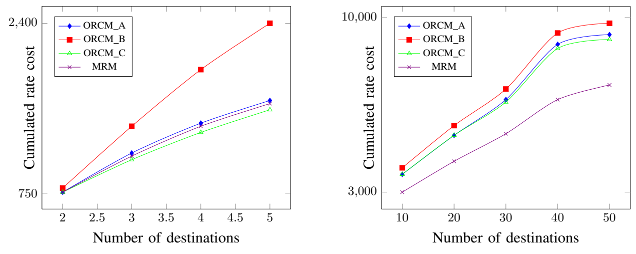


(a) For small numbers of destinations (5)



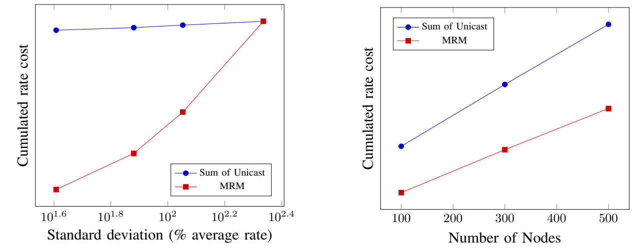
(b) For large numbers of destinations (10)

Fig. 5. Impact of the rate distribution on the global routing cost

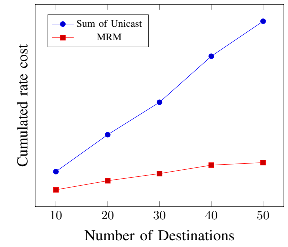


(a) Small numbers of destinations (b) Large numbers of destinations

Fig. 6. Variation of the number of destinations (among 500 nodes)



(a) Rate distribution (b) Network size



(c) Number of destination

Fig. 7. Comparisons of MRM and sum of unicast

Fig. 7(b) and 7(c) show the impact of varying the number of nodes and the number of destinations, respectively. In both cases, the MRM rate cost increases slower than the sum of unicast costs. This is reasonable since more destinations and more nodes imply more opportunities to share a common path.

V. CONCLUSION AND FUTURE WORK

Two multiratecast protocols, MRM and ORCM, were proposed in this paper. These protocols are specifically designed for wireless sensor network scenarios where different destinations can request a same data at different rates. Both are position-based and localized protocols that extend the greedy-face-greedy routing principle to the multirate context. Their differences lie only in the way they select the next forwarding neighbors at each hop, in greedy mode. The main idea behind MRM is to select the neighbors that best serve highest rate destinations, while ORCM evaluates several forwarding choices and then select the best, according to a given evaluation method (three were proposed). If the number of destinations is under a given threshold, then ORCM evaluates all possible choices, else it evaluates only a part of them according to a well-defined process. Since the transmission rate can be different at each relay node, we stated that the traditional *hop count* and *number of transmission* metrics were not appropriate to measure the efficiency of multirate paths, and introduced a new rate-based metric. This metric was then used to compare the behavior of the two proposed protocols in various scenarios (by varying the network size and density, the number of destinations, and the distribution of rates among destinations). Simulation results shown that one of the three evaluation methods for ORCM (ORCM_C) outperformed the two others in all scenarios. Regarding the comparative performance of ORCM_C and MRM, we observed a slight advantage for ORCM_C in case of *small* numbers of destinations (that is when ORCM evaluates all possible choices), and a stronger advantage for MRM in case of *large* numbers of destinations. Finally, MRM has also a low computational cost.

A number of research directions can be considered after this prior work. A first one would consist in releasing some assumptions, such as the capability for each node to potentially deliver the maximal required rate, or the fact that node movements are not expected within the time of one single routing task. Another possible adaptation is to consider multiple sources as well as multiple destinations, and to develop a dedicated merging scheme for data. Now, regarding the evaluation of multiratecast protocols, an important improvement would be to compare the generated paths with optimal reference paths. Since the problem is NP-complete, an interesting prospect would be to design a centralized approximation algorithm capable of generating such reference paths, with and without the wireless advantage.

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