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2.5 Layer Protocol for Traffic Regulation in Ultra-Dense Nanonetwork

Traffic Regulation in Ultra-Dense Nanonetwork

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Abstract The nano terahertz networks represent one of the promising areas in the field of wireless telecommunications. Technological advances in miniaturization of antennas and terahertz communications have paved the way for new network applications such as the body network, the programmable material and multi-core processors. Some of these applications require the concentration of a very large number of tiny nodes in a limited space. In this ultra-dense context and in the absence of centralized access control units, we propose to implement a distributed strategy of spatial and temporal traffic regulation to guard against the risks of congestion, interference and energy over-consumption. In this paper, we propose a protocol for optimizing terahertz radio links using beam steering antenna, distributed time division technique and sleep mode in order to reduce the flow of redundant traffic over the network, smooth the volume of communications exchanged over time, and preserves the lifetime of the nodes.

Keywords Terahertz Nanonetwork · Ultra Dense nanonetwork · directional antenna · MAC Layer

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1 Introduction

New network applications have emerged in recent years driven by major advances in the miniaturization of electronic devices and radio antennas. In ultra dense nanonetworks, a very large number of radio devices are confined in a small space. In this context, the Terahertz frequency band has the double advantage of combining a high bandwidth with a low energy and coverage range. The use of short-range terahertz communications finds many applications in the field of massively multi-core computer architectures [2] and programmable material [1].

Due to the limited computation and energy capabilities of the nanonetwork nodes (sub-millimeter scale), the multiple access protocols must meet simplicity and scalability requirements. Access to the channel must be done with a reduction of the number of control messages and without resorting to centralized entities. To this end, several innovative techniques have been proposed such as: PHLAME [3], ASRH-TSOOK [4], HLMAC [7], DRIH-MAC [8], etc. However, in view of the extreme density of the network, the classical multiple access protocols are not sufficient to spread the traffic load and to control the multi-hop flows on the network. Indeed, given the density of the network, the message broadcast causes numerous feedback loops that saturate the system (broadcast storms).

The traffic regulation protocol is seen as a 2.5 networking layer that allows to extend the access control layer missions with some routing considerations. The traffic regulation amounts to defining a logical topology of the network starting from the physical topology where any two nodes can communicate when they are within range of each other. The logical topology designates a subset of neighboring nodes which can communicate in a predetermined direction and at predetermined time. Formally, the logical topology represents a directed sub-graph of the physical topology. The logical topology is said robust when the directed sub-graph is strongly connected. The connectivity degree of the sub-graph could be used as a measurement of the logical topology robustness. A directed graph is said k-connected if it remains connected whenever fewer than k nodes are removed.

Traffic regulation protocols for ad hoc networks have been widely studied in the literature [5,6,9]. One of the best known is the Optimized Link State Routing Protocol (OLSR) [5]. However the adaptation of this protocol in the case of an ultra-dense network is complicated. OLSR is based on the exchange of neighboring lists between nodes. Due to the density of the nanonetwork, those lists are heavy to transmit and difficult to store or to process. Other protocols aim to define a spanning tree over the network's nodes [10]. The logical topology of the network represents then a tree where the nodes close to the root concentrate more traffic then nodes near the leafs. Therefore these protocols are adapted when the physical structure of the network involves different types of nodes : simple nodes and super-nodes like in Wireless Body Sensor Nanonetwork architecture [11]. In addition, such protocols present only one path to link every two nodes, which makes the logical topology unreliable.

By conclusion, few works from literature deal with traffic regulation in dense homogeneous ad hoc networks.

Our proposed protocol has three main objectives. First, traffic load evolution presents peaks that lead to congestion phenomena. The principle of communication by appointments allows to spread the traffic and to schedule communications in time. Secondly, dense networks present various path to transmit data from one node to another. In terms of routing (layer 3), this implies a greater complexity of choice. The risk of local congestion on the network is therefore higher and more redundancy is expected (multiple receptions of the same message by the same node). The use of electronically steerable antennas improves the control of the transmitted radio signals (interference). Moreover, each node selects the subset of neighboring nodes with which it can communicate directly. Finally, communication by appointment allows nodes to plan their waking and sleeping periods. In addition, the energy consumed by communications is reduced because the emission power is channeled in specific directions at given periods. Finally, only a subset of covered nodes are selected as sources or successors nodes and messages of not selected sources are ignored (not delivered to the layer 3).

In this paper, we propose an original procedure for the Layer 2.5 networking protocol that takes into account the terahertz frequencies particularities in a dense context. The idea is to extract a logical topology from a dense homogeneous nanonetwork that allows to both reduce the number of direct communication links and maintain the robustness against temporal nodes unavailability. This procedure exploits the available antenna steering techniques to schedule over time and space the data transmission. Unlike the other approaches, our method does not impose any conditions on the physical platform and presents, according to our knowledge, the first 2.5 networking layer protocol adapted for terahertz nanonetworks.

2 Traffic regulation problem modeling

Let W be a nano wireless network composed of N nodes. Each node in the network has a reconfigurable directional antenna that can be steered dynamically to cover a particular direction. Let T_{ch} be the time needed to change the orientation of an antenna. Let $G(X, A)$ the connected graph describing the physical topology of the network with X the set of nodes ($|X|= N$) and A the communication links between the nodes. $(x, y) \in A$ means that there is a particular configuration of the x and y antennas that makes the two nodes communicate directly.

2.1 Traffic regulation constraints

The traffic control problem consists of calculating a directed sub-graph $G'(X, E)$ with $(x, y) \in E \to (x, y) \in A$ where the following conditions are satisfied:

– G' is strongly connected: given two nodes in the graph, there is a way to route the data from one node to the other in the two directions.

$$\forall x, y \in X^2, \exists \text{ a path from } x \text{ to } y \tag{1}$$

– G' is robust: whatever the node, there are enough ways, p, to receive the data from the other nodes and enough means, s, for the node to broadcast its own data. The values p and s denote the desired level of robustness represented by the number of predecessors and successors of each node. Choosing a large value of p and s allows a higher level of robustness that derives from the reliability level of the nodes. When nodes are prone to a high risk of outages or if the energetic capacity of nodes makes it regularly in charging phase, then a high value of p and s is more suitable.

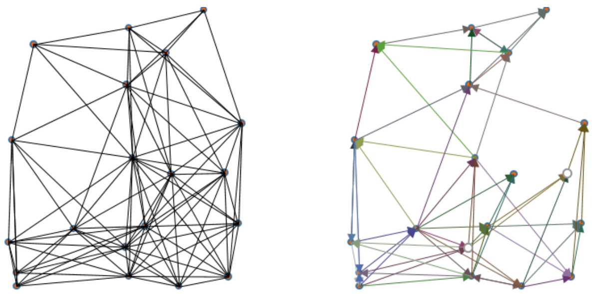

Fig. 1 Traffic regulation problem: from physical to logical topology

2.2 Antenna steering and sleeping mode

Each directed edge (x, y) of the logical topology G' have two index values S_{xy} and S_{yx} designating the period of time (relatively to each node) during which x and y can communicate according to a particular orientation of their antennas. Each node changes its antenna configuration (orientation), in a cyclic manner and at a regular interval of time, $T_s; T_s >> T_{ch}$. During the period S_1, the node x uses the configuration $C_{x,1} \in C$ then during the period S_2, it uses the configuration $C_{x,2}$ and so on. At the end of the period S_{NS} (NS being the number of slots in one cycle), the node x returns to the configuration $c_{x,1}$ for a new period S_1 and the cycle restarts as depicted in Figure 2. The duration of a complete cycle T_{cycle} is identical for all the nodes (See Equation 2). Certain periods S_i may correspond to periods of time during which the communication devices are deactivated. Moreover, the cycle of a node can have several periods with the same parameter ($i \neq j, C_{x,i} = C_{x,j}$).

$$T_c = NS \times T_s \tag{2}$$

For a given period S_i, a node x is either in listening, transmitting or sleeping mode. For each listening period S_i of x, there is one and only one node $y \in X$ such that $(y, x) \in E$, and $S_{xy} = S_i$, which means that there is only one listened node at a time. If the period S_i is a transmission period of x, then there is at least one node y such that directed edge $(x, y) \in E$ and $S_{xy} = S_i$. Sleeping mode corresponds to periods of time where the node x has no directed edge $(x, y) \in E$ or $(y, x) \in E$ with $S_{xy} = S_i$, which means that the node is not listening and not transmitting.

Given the asynchronous nature of the network, the index of a period S_i of a given node has only a local signification. The figure 2 shows an example of traffic regulation involving 5 nodes. The node (A) has two active periods S_1 in transmission and S_2 in reception. The period $S_1 = S_{AC} = [0.3 - 0.4]$ covers 1/10 of the cycle time T_c between instants $0.3 \times T_c$ and $0.4 \times T_c$. During this period, the node (A) covers the node (C) which is listening during its period $S_3 = S_{CA} = [0 - 0.1]$ as well as the node (E) which listens during its period $S_1 = S_{EA} = [0.7 - 0.8]$.

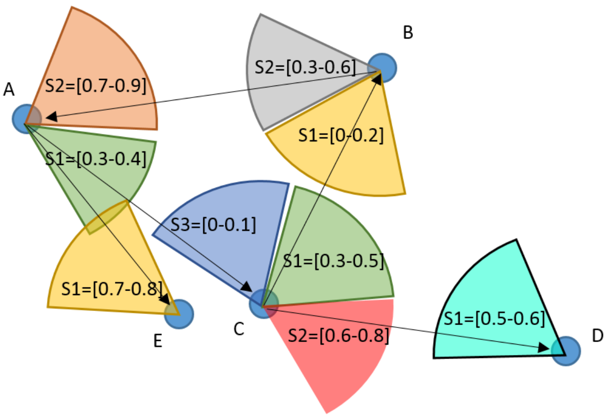

Fig. 2 Example of TDMA synchronization: each edge (x, y) is indexed by the index of the transmission period on x (S_i) and the index of the reception period on y (S_j). Each period $S[tb - te]$ is designated by its beginning and end time (the time is given relatively to the concerned node). The colored arcs display the antenna orientation at the corresponding period.

When two edges $(x, y1)$ and $(x, y2)$ with the same tail have the same index value on x, the two incoming nodes $y1$ and $y2$ are then served by the same multicast stream. By the way, the edges $(x1, y)$ and $(x2, y)$ with the same head can not have the same period index on y in order to avoid interference. For all the edges $(x, y) \in G'$, the associated listening period on y must be equal to the duration of the transmitting time on x in order to maximize the sleep periods.

Along with the respect of traffic regulation constraints, in particular the connectivity and the robustness of the sub-graph G', the traffic control algorithm must take care to maximize the useful listening and transmission times, T_i, ($T_i \subset S_i$) as well as the sleep periods of the nodes. A transmission period of a node x is said to be useful when throughout all its duration, all nodes $y, (x, y) \in E$ are at listening mode. A listening period of a node y is said useful when throughout its duration, the listened node (there is only one) is in transmission phase to y.

2.3 Traffic regulation in Terahertz network

In DAMC modulation technique [12], the terahertz frequency band is mainly subdivided into three frequency windows which are allocated according to the transmitter-to-receiver distance which is either short, mid or long. To take into account this particularity, the traffic regulation protocol associates with each active period a coverage range: short, mid or long. Then, only nodes with a distance in the selected range are considered to be successors. At a given transmitting time slot, the successors of a given node are all in the same range, allowing to use the same optimal frequency window to serve them (See Figure 3).

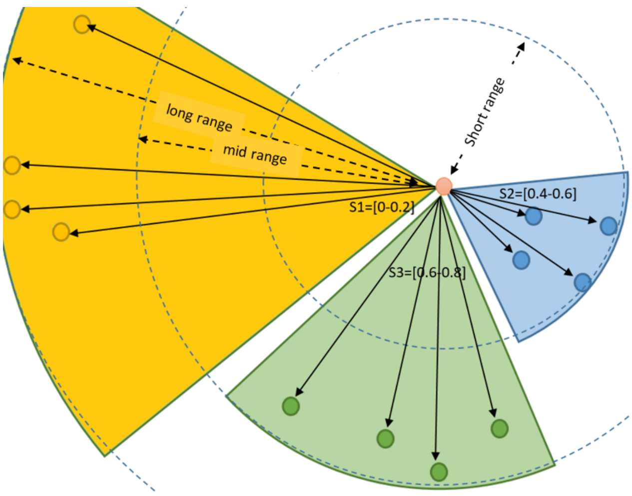

Fig. 3 At every period, the transmitting node selects its successors according their distance from the node in order to optimize the used frequency window. The colored arcs represent the orientation and coverage of the node at a given period.

3 Distributed algorithm of traffic regulation

The algorithm 1 represents our traffic regulation protocol. The design of the algorithm aims to satisfy two main constraints: a reduced computation requirement and limited messages exchange. When a node wants to join the nanonetwork, it defines for each slot a covering range (short, mid or long). Then, the node alternates between two modes. In the first mode, the node listens to the channel and switches over the set of configurations $C = \{C_1..C_{NS}\}$ with a frequency of $1/T_s$. In the second mode, the node launches invitations in different directions looking for successor nodes and changes its configuration with a frequency of $1/T_c$. The use of two different reconfiguration speeds aims to prevent the hidden node problem.

In successor search mode, the node keeps the same antenna configuration during all a cycle T_c of NS slots T_s. The value of NS depends on several parameters such as the reconfiguration delay T_{ch}, the cycle duration and the number of needed sources and successors. In our tests, we have set $NS = 14$. At each period T_I, the node launches invitations. After each reception of an acceptance, the source updates its useful transmission period, its coverage list and sets the period mode to 'transmission' mode. Nodes in source search mode, listen for any invitations. Based on the target range of the source, the strength of the received signal and the remaining listening time, the node chooses to accept the invitation or not. In case of acceptance, the node registers the useful listening period. Once the number of necessary source nodes is reached (parameter p), the node stops using the source search mode.

To avoid a slow start when few nodes are active, the number of listening and announcement cycles is limited to M. After every M ordinary operating cycles, a node with not enough sources (resp. successors) listens (resp. resends invitations) during an entire cycle. These two procedures allow nodes that start very early or late compared to the other nodes to complete their lists of prefixed links.

The disconnection of the graph $G'(X, E)$ is avoided thanks to a long-term procedure which provides that each node, at a very important time interval, listens in all directions whether neighboring nodes belong to other connected components. For this purpose, the nodes of the same connected component share an identifier of the component which corresponds to the smallest MAC identifier of the nodes belonging to the component. When a node detects a neighboring node with a different component identifier, a connection procedure of the two nodes is started.

4 Tests and results

To study the impact of the traffic regulation algorithm over dense nanonetworks, we have established several test scenarios, which are differentiated by the number of nodes, the spatial dimension of the network, the range of the radio signal and the density of the network. We first begin by evaluating the impact of traffic regulation on network performance in terms of interference. A first indicator of the impact on interference is the comparison of the number of edges in the graph $G(X, A)$ and the number of edges in the graph $G'(X, E)$. When $|E| << |A|$, the average number of signals arriving on each node is reduced considerably. Interference reduction also benefits from time

Require: T_s, T_c, $t0$, NS, $P = \{C_1..C_{NS}\}$, $T = \emptyset$, $nbcycles = 0$, $t0 = now()$, $nbsec = 0$, $nbsrc = 0$

for i $\in$ {1 to NS} **do**
  $rng_i = rand(1..3)$; $param_i = \emptyset$;
  $cov_i = \emptyset$; $mode_i = \emptyset$
end for
//research phase of the successors
for i $\in \{1..NS$ each T_c } **do**
  if $nbsuc < s$ **then**
    antenna parameters $\leftarrow C_i$
    for j $\in \{1..NS$ each $T_s\}$ **do**
      if $mode_j = NULL$ **then**
        left=$t0 + nbcycles * T_c + j * T_s - now()$
        send $invit(me, left, rng_j)$ each T_I
        for each $accept(n, t)$ **do**
          $nbsuc + +$; $mode_j$='trans'
          $cov_j = cov_j \cup n$; $param_j = i$
          $T_j.begin = now()$; $T_j.end = min(T_j.end, now() + t)$
        end for
      end if
    end for
    $nbcycles + +$
  end if
end for
//research phase of sources
if $nbsrc < p$ **then**
  for i=1 to NS with frequency T_s **do**
    begin=$t0$+$nbcyles \times T_c + (i - 1) \times T_s$
    end=begin+T_s
    antenna parameters $\leftarrow C_i$
    if $mode_i = NULL$ **then**
      while $end - now() > minCom$ **do**
        //remaining time is enough
        for each invit(node,t,rng) **do**
          if distance(node, me) $\in$ rng **then**
            send accept(me, min(t,end-now()))
            $nbsrc + +$; $mode_i$='listen';
            cov_i=node; $param_i$=i
            useful time $T_i = [now(), now + min(t, end - now())]$
          end if
        end for
      end while
    end if
  end for
  if $mode_i = NULL$ **then**
    $mode_i$='sleep'
  end if
  $nbcycles + +$
end if

Algorithm 1: Every M successive cycles division access mode, beam control antenna and selectivity of listened sources. All these factors make it possible to reduce the risks of massive arrival of communications at the same time on the same node.

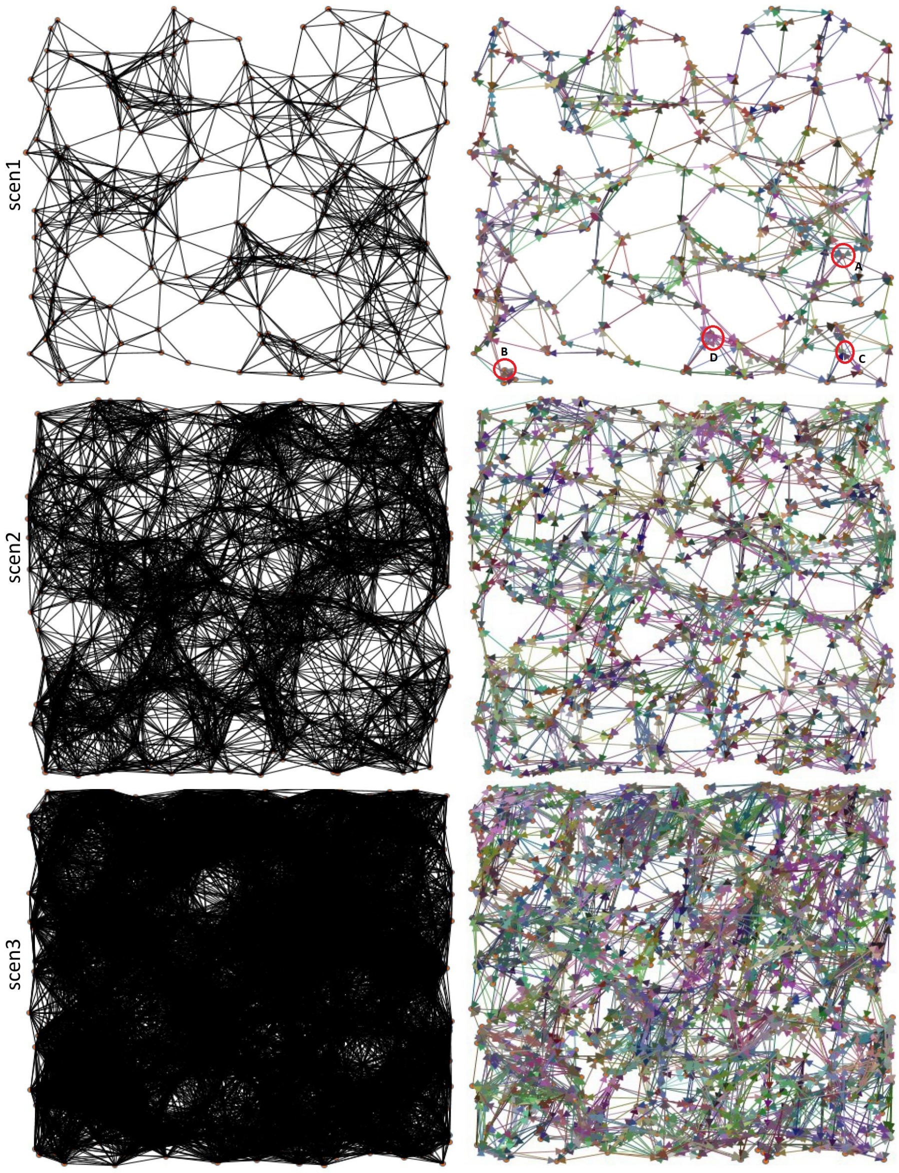

Fig. 4 Traffic regulation for 3 scenarios: 200 nodes, 500 nodes and 1000 nodes. Tests are implemented using Microsoft Excel VBA.

Figure 4 presents three simulations of traffic regulation using different number of nodes 200, 500 and 1000 in the same area using Microsoft Excel VBA. For each scenario, on the left, the graph $G(X, A)$ shows the physical topology of the network and on the right the graph $G'(X, E)$ is obtained by the traffic control algorithm 1. The traffic regulation is carried out with the maximum number of sources equal to $p = 4$ and the maximum number of successors equal to $s = 10$. For Scenario 1, the traffic regulation algorithm reduces the density of the graph from 1202 edges to 744 edges, i.e. a reduction of 38%. For the Scenario 3, the traffic control algorithm reduces the graph from 30891 edges to 3997 edges, which corresponds to a reduction of 87%.

We also assess the impact of traffic regulation on network data broadcasting. To this end, we have selected three evaluation criteria: The total number of receptions including redundancies, the maximum number of receptions of the same message on one node and the time for a total broadcasting of the message. According to the first two criteria, the traffic regulation allows to improve the behavior of the network when a node broadcasts a message over the network. Regarding the total number of messages received by the nodes, an approach without traffic regulation will generate for the scenarios 1, 2 and 3 respectively 2404, 15082 and 61618 messages. The number of receptions with traffic control decreases to 744, 1997 and 3997 messages respectively. The maximum number of reception of the same message varies in the approach without traffic regulation between 24, 45 and 96 for the three scenarios whereas with traffic control, it remains 4 for all three scenarios. This corresponds to the value of the maximum number of sources: parameter p.

The number of hops allowing all nodes to receive the message is also a crucial factor for the performance of the traffic control algorithm. The simulations show that the total diffusion of a message depends on the position of the source node in the network. We studied 4 different placement of the source nodes for the Scenario 1, shown in Figure 4, circled in red and labelled A, B, C and D. Broadcasting without traffic regulation from node (A) requires 9 hops while 14 hops are required with traffic control. Similarly, the application of traffic control requires respectively 26, 18 and 22 hops to broadcast a message from the nodes (B), (C) and (D) instead of 12, 12 and 9 jumps without regulation traffic. For Scenario 1 which is the least dense, the number of hops for the total broadcast doubles with traffic regulation, a negligible additional cost in return for reducing the total number of exchanged messages.

5 Conclusion

In this paper, we have proposed a novel distributed protocol for optimizing the logical topology of homogeneous, ultra-dense terahertz nanonetworks. The objective of this optimization is to reduce the amount of interferences due to the concentration of numerous nodes transmitting in all directions at random instants. The logical topology we proposed fixes for each node the moments during which it can send data in a given direction to given selected destination nodes. Each node ignores messages sent by nodes that do not belong to the predefined subset of neighbors, which reduces the energy consumption.

Furthermore, the reduction of direct communication links between nodes does not impact data broadcasting coverage. Simulations show that the diminution of the broadcasting speed is limited compared to the gain in terms of transmission redundancy and generated interferences.

Finally, the traffic control protocol is adapted to the DAMC protocol used for terahertz communication. The successors of a given node in a specific direction are in the same range of distance from the transmitter. Therefore, all the nodes covered in the same direction are served by the same frequency channel. The distance between nodes and their successors varies according to the transmission direction leading to a better use of the terahertz band.

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