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1- # A Study of Distributed Control In Cellular Radio Networks

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4- **ABSTRACT**

The increased processing load experienced in centralized controlled cellular systems of the first and second generation is discussed. The necessity of distributed control is established, and solutions utilizing the concept of distributed control are surveyed. A discussion of a proposed new structure for cellular networks is presented, followed by the appropriate multiple access scheme to be used in such networks.

I. INTRODUCTION

As with any other communication industry, cellular systems make use of the state-of-the art technology. For instance, voice recognition is currently being employed as a natural network feature in MetroCel Cellular, Dallas, USA [7]. The literature contains suggested changes and enhancements to the cellular networks [1], [2], [6]. These changes include changing the infrastructure of the cellular system, and implementing new services within existing networks. There is literature on Mixed Media Cellular Networks e.g. [5] & [6], where the traffic models and performance parameters for cellular voice-data system are formulated. However, in this paper our purpose is to discuss whether the cellular system architecture, based primarily on centralized control can cope with the growing demands on cellular phones and personal communication systems. The need for distributed control is detailed in section II. Then, in section III we identify the basic control functions that are intended for distribution among the system elements. A brief discussion of the available alternatives for distributing these control functions are presented. Sections IV & V discuss the application of distributed control to a new generation of cellular radio network proposed in [1] & [2]. Section VI introduces the multiple access scheme to be used in conjunction with the proposed networks. Section VI is a conclusion.

II. THE NEED FOR DISTRIBUTED CONTROL

While the first generation analog cellular systems support a traffic density of about $1 E/MHz/km^2$ and the second generation digital cellular systems (GSM) support up to $10 E/MHz/km^2$, it is expected that by the end of this century the traffic demand will reach as high as $5000 E/km^2$. This will require cellular systems capable of handling demands in the order of 100's of $E/MHz/km^2$. It might appear that the successive use of cell splitting and frequency reuse would be capable of fulfilling such excessive demands. However, this is not true for two reasons.

First, there is a limitation on the minimum cell radius imposed from cell site position tolerances (cells are not forming regular hexagonal shapes as the design aims) which leads to the practical limitation of 1 mile cell radius in conventional analog cellular systems [4].

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Second, the network control subsystem imposes a severe limitation on cellular systems. Although attempts to build micro cellular systems in which the cell radius can be reduced by virtue of strict transmitter
power reduction and control, the frequent movements of the mobile units across cell boundaries in such units impose a great load on network control. The main reason for the control load increase is the growing need to perform handoff operations, which is equivalent to a new call set-up. The blank and burst technique discussed in [4] will result in audible clicks increasing and resulting in an unacceptable performance. The *Mobile Telephone Switching Office* (**MTSO**) is responsible for performing all handoff functions for the whole network (e.g. reception of level degradation messages, checking levels in surrounding cells, choice of new cell, and channel allocation in new cell). With an immense increase in handoffs, it is expected that the MTSO processing capabilities will saturate.

In the second generation GSM system, an attempt to ease the processing load required for the handoff procedure was made. The GSM employs what is called *mobile assisted handoffs* in which the mobile terminals sends to a *Base Station Controller* (**BSC**) information about the signal strengths received from various *Base Transceiver Station* (**BTS**) lying in the area controlled by this BSC. It is the BSC, not the MTSO (or in GSM terms the *Mobile service Switching Center* (**MSC**)), that performs the assisted decision [9]. Mobile assisted handoffs may be viewed as the first step towards distributed control.

Another development in the control architecture of the GSM network was the dedication of a number of channels intended for the exchange of control information during a call process. This is contrasted with the blank and burst technique that is used in analog cellular systems. Although these control channels increase the call processing capacity of the system, they do not reduce the load imposed on the MSC.

Furthermore, the centralized controller (MTSO or MSC) performs various control functions. In addition to handoff functions the MTSO receives call requests from the cell sites, identifies and validates users for incoming calls, determines channel selections, keeps record of all call information for billing and administration, and finally it monitors system performance including diagnostics and alarm for cell site equipment [8].

III. CONCEPT OF THE DISTRIBUTED CONTROL

Having established the need for distributed control in section II, it is important to identify the main control functions performed in a mobile network. Such an identification is needed to determine which functions are to be distributed. These control functions may be divided into three categories.

1) *Call management* which is not unique to wireless networks. It is a basic function in all fixed networks responsible for call initiation, termination and routing. The design of a cellular packet switch should aim at making use to the greatest extent of the capabilities of the fixed network without requiring any modifications to these networks. The cellular packet switch should be transparent to call management functions.

A proposed method for distributing call management functions in cellular radio network is the use of *interface points* that connect the mobile network directly to the public switched telephone network [8]. This will allow the existing wireline network to serve as the backbone of the cellular network and to perform the common functions required by both networks.

2) *Mobility management* which includes the functions necessary for location updates and handoffs. These functions, originally performed by the MTSO in the analog (first generation) cellular networks, will be supported in a distributed control network by a pair of data bases, as explained in the next section, without the need for intervention of the fixed network. This technique is similar to that used in the GSM standard for digital radio [9].

3) *Radio resource management* including all functions necessary for control of the radio channels and the time slots e.g. channel allocation, channel quality monitoring, power control and media access.

One alternative is to distribute most of these functions among the base units and the wireless terminals, while some will still be supported by a cellular controller.

Another alternative is to allow *net* operations in which the mobile terminals are allowed to communicate with one another directly without the intermediation of a base controller except possibly during call set-up. This has several advantages including the increased spectral efficiency (*one* channel is used for *two* mobile users), the robustness due to the ability to communicate even after a controller failure, and the ability to use the mobile terminals as radio relaying stations if necessary allowing additional path redundancies. The disadvantages of such an approach are quite severe though, freeing the mobile terminals from the control of the base station also implies that interference regulation, power and timing control can no longer be performed. Thus fade margins have to be increased in order to guard against uncontrolled interference. Another disadvantage is that *net* operation, specially when used in conjunction with TDMA or CDMA access schemes will lead to potential increase in the cost and complexity of the terminals.

This categorization and division of the main control functions of the network are the basic goal and the unique feature of the cellular packet switch design (discussed in the following section) since this division makes the system capable of supporting the ever-growing control load within the network.

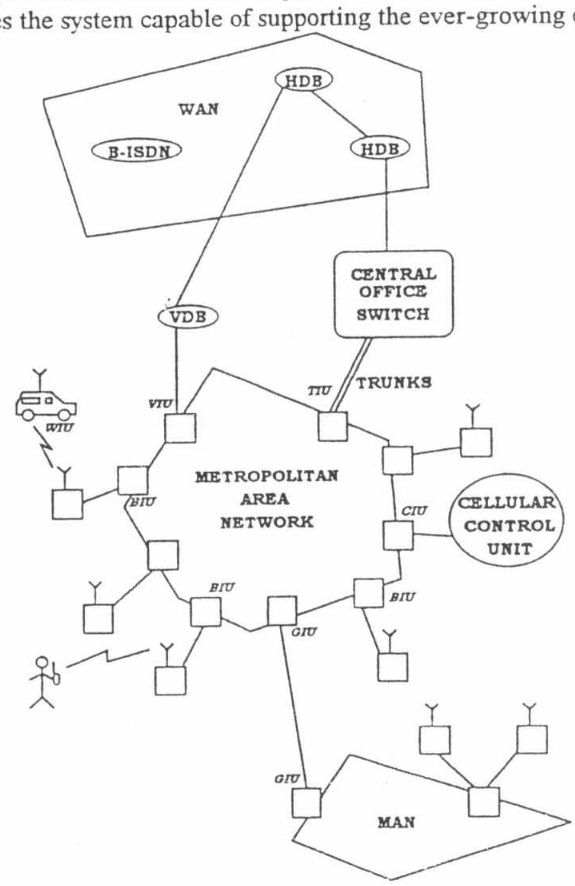

Figure 1 Cellular Packet Switch Architecture

IV. CELLULAR PACKET SWITCH ARCHITECTURE

In 1990, David J. Goodman proposed a distributed control system as a model for third generation cellular systems [2]. In 1994, the allocation of the control functions to the elements of the cellular packet switch was performed in [1] in order to arrive at specific protocols for call set-up, handoffs, and location updating. The proposed infrastructure of the network will be first explained.

Referring to figure 1 the network can be viewed as a Metropolitan Area Network (MAN) linking base stations, data bases, public central office switches and a cellular controller. Several interfaces between the various elements of the network exist for controlling information exchange between the various elements of the network.

The basic functions performed by each network element, and the interfaces linking these elements are described below.

1) *Central Office Switch:*

It is a part of the public switched telephone network or it may also be a private branch exchange that owns its own connections and trunking to the public network. The central office switch performs all call management functions that include, call set-up, call release, routing, and billing. A cellular packet switch will be typically connected to more than one central office switch.

2) *Trunk Interface Unit (TIU)*

It interfaces the central office switch to the cellular packet switch. It accepts information from the central office in the format of the public network, e.g. 64 kbps companded PCM for speech. This information is then converted to the format accepted by the radio link via a transcoder. The number of TIU's in the network will be equal to the number of central office switches to which the cellular packet switch is connected.

3) *Cellular Controller*

Although the cellular packet switch is based on distributed network control, some operations require central coordination. These operations are performed within the cellular controller. Network control packets are generated, received, and processed by the cellular controller. For each call, it assigns a virtual circuit identifier and sends this identifier to the TIU and to the Wireless terminal Interface Unit (WIU) to initiate the call as will be explained. The controller contains an administrative processor to test all the MAN interface units. This processor also monitors traffic on the MAN and performs the statistics necessary to study the utilization of the network elements. The cellular controller is also responsible for the coordination of channel management and the rearrangement of the assignment of channels to base stations according to traffic changes.

4) *Cellular Controller Interface Unit (CIU)*

The CIU is responsible for the distribution of the virtual circuit identifiers assigned by the cellular controller to the TIU (using the TIU's permanent identifier) and to the WIU using the base station identifier in the destination field of the control packet and the wireless terminal permanent identifier in the information field of the control packet.

5) *Base Stations*

As in conventional cellular networks, the base stations contain the radio equipment and the antenna systems for communication with the wireless terminals. However, this communication is not through dedicated channels but through packets. The protocol which is used for multiple access of the radio link is the *Packet Reservation Multiple Access* (**PRMA**). PRMA is a known multiple access technique which was chosen for use in combination with the cellular packet switch as a base station to wireless terminal transmission protocol. PRMA will be briefly explained in section VI.

6) *Base station Interface Unit (BIU)*

This unit is the interface between the MAN and the base stations. It relays information between the wireless terminals and the TIU's. It multiplexes information packets that are sent to the radio transmitter and queues the upstream packets for transmission over the MAN. Each BIU has a permanent identifier with which it is always addressed.

7) *Wireless terminal Interface Unit (WIU)*

This interface is connected directly to the user, it generates packets and delivers them to the radio transmitter under control of the PRMA protocol. The WIU should be able to implement terminal initiated handoffs, which is the key point in releasing the excessive control load experienced in conventional systems. In order to fulfill this requirement, the WIU refers a channel quality monitor that indicates the identity of the base station best able to serve the terminal in its current location. Terminal initiated handoffs will be further explained in section V.

8) *Gateway Interface Unit (GIU)*

Gateways connect Two MANs and permit traffic to be passed between the two MANs according to the desired connections. A Gateway interface unit interfaces the gateway to the two MANs on both sides of the gateway. The main function of the GIU is the conversion of virtual circuit identifiers (VCI) between the two networks.

9) *Data bases and there interfaces*

There are two types of data bases in the proposed cellular packet switch and its network control protocols. the purpose of these data bases is to facilitate the task of locating the mobile and to keep record of user information as with any ordinary stored program controlled exchange.

The first type of data base present is the *Home Database (HDB)* which contains information pertaining to a large group of subscribers. In order to determine the current location area of the subscribers it holds a pointer to the visitor database in which the subscriber is currently located. The location of the HDB is proposed to be in the fixed infrastructure of the network. The interface to the HDB is the *Home database Interface Unit (HIU)*.

The second type of database is the *Visitor Database (VDB)* which is in charge of a certain location area. As a mobile terminal moves into a location area belonging to a certain VDB, it registers itself in this location specific VDB. This VDB then contacts the HDB and the HDB pointer mentioned earlier points to the is specific VDB. The VDB then obtains all necessary subscriber information from the HDB. The interface to the VDB is the *Visitor database Interface Unit (VIU)*.

V. Organization of information flow

Having discussed the basic elements comprising the cellular packet switch and the main control functions necessary for its operation and there distribution among these elements, the organization of user information and system control information will be discussed below.

Since we shall be concerned with the flow of packets through the network, we will use a symbolic representation for the packets that makes an analogy between a packet and a post card. This symbolic representation is given in figure 2.

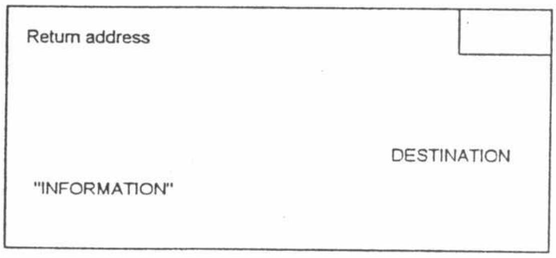

Figure 2 The packet-postcard analogy

The information flow can best be illustrated by giving examples of conversation, handoff and mobile initiated call setup. These are the basic situations encountered in a cellular environment.

① **Mobile unit initialization**

In section IV the way in which the mobile unit identifies its location in the MAN was implicitly discussed in the functions of the HDB, and VDB. The mobile terminal registers itself into a specific VDB as it moves into its service area. Subsequent updates to the HDB is done through the VDB.

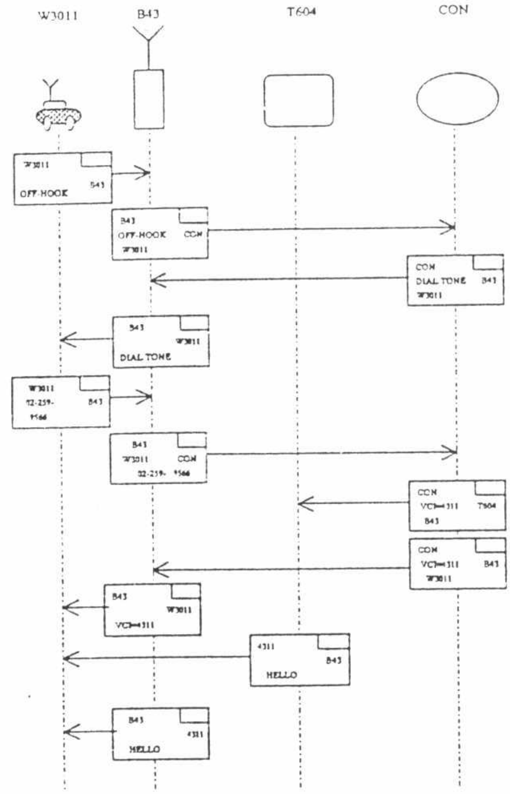

Figure 3 Mobile initiated call

② **Mobile terminal initiated call set-up**

1) the mobile terminal sends an "off hook" message to the nearest cell site. The nearest cell in figure 3 is B43

2) The base terminal sends the off hook message along with the identity of the wireless terminal to the VDB specific to the current location. In order that the VDB responds to the same BIU, the Virtual Circuit Identifier (VCI) of the BIU is also sent to the VDB.

4) The VDB should contain information about this mobile terminal from previous registration and location updates. The VDB now searches through this information to determine if this mobile is authorized to place a call. This is called the authentication procedure.

5) To complete the authentication procedure, an authentication request is sent by the VDB. This request is in the form of a certain random number which should be used in conjunction with the authentication key to compute an authentication response message.

6) Without waiting for a response from the VDB, the mobile unit sends its own phone number and the dialed numbers to the VDB.

7) If the VDB receives the correct response to its request, the mobile terminal should be granted service. Consequently, it forwards a request for a virtual circuit identifier to the cellular controller.

8) The cellular controller assigns a specific VCI to this call, and informs the VDB with this VCI.

9) The VDB sends all its current information regarding this call; calling number, called number, the VCI specific to the BIU nearest to the mobile, and the mobile terminal visitor data base record to the TIU to start the call. The central office switch assigns a voice trunk to the call and the TIU maps the call VCI to this voice trunk.

10) The TIU sends a call proceeding message to the base terminal. The BIU sends the mobile phone number and virtual circuit identifier to mobile terminal. Thus the mobile terminal records the VCI for subsequent use.

③ Mobile terminated call set-up

1) The originating switch receives the called number from the calling party and forwards it to the WAN using a standard signaling system; namely Signaling System number 7 (SS7). The called number is identified as a mobile number.

2) The destination phone number is used as a key entry to the HDB which returns to the same signaling point within the SS7 network data on the mobile. Which data will most probably be the local telephone number which the mobile received during the registration process.

3) The information obtained from the HDB is used to determine which switch will be the destination switch . The circuit switched network routes the call to this destination switch.

4) The destination switch contacts the location specific VDB in which the mobile is registered. The VDB recognizes the local telephone number.

5) The VDB broadcasts the paging message to all BIUs within its location area and waits for a response.

6) The mobile unit identifies its own local telephone number and sends a page response message to the BIU from which it received the paging message.

7) The authentication procedures for the mobile is performed in the VDB when it receives the page response from the relevant BIU. If the authentication succeeds i.e. the mobile terminal is found authorized to use the network, the VDB requests a VCI from the CIU. It then sends an authentication success message to the TIU containing the VCI number chosen by the cellular controller.

8) The TIU forwards the VCI of the call (obtained in 7) and the permanent VCI of the base to the central office.switch. The central office switch reserves a channel between the switch and the TIU. The TIU maps the call VCI to this allocated channel.

9) The setup message is sent to the BIU. The base station stores the VCI as one of its calls. The setup message is then forwarded to the mobile, notifying it with the chosen VCI and causing the mobile phone to ring.

④ Handoffs

As mentioned earlier, one of the main advantages of the cellular packet switch is the ability to perform handoffs without the need for the intervention of the cellular controller. Basically, there are two types of possible handoffs within the cellular switch with respect to the relationship between the new and old base stations. First, intra-MAN handoffs which are performed between the base stations belonging to the same MAN. Second, inter-MAN handoffs in which two MANs are involved, these require a MAN gateway. The handoffs can also be mobile initiated or base station initiated. Only intra-MAN mobile-initiated handoffs will be discussed here as an illustration to the way in which the control is distributed through the network.

1) The mobile terminal notices that the voice quality has reduced to its minimum allowable level. It determines according to a certain radio protocol the desired new base station. Let it be BIU30.

2) While the mobile is tuning to the new base station, or in other words, while the radio protocol is providing link layer resources; packets received by the old base station are lost.

3) The new base station BIU30 receives a handoff message which includes the old BIU. It recognizes this previous BIU to belong to the same MAN and proceeds to create a table entry to include the VCI of the ongoing call as one of its calls.

4) The handoff message is forwarded from the new BIU to the TIU to determine which data packets were lost (were sent to the no-longer-active old base station). Voice packets are not retransmitted and this may not be noticeable due to their short duration.

5) The new base sends a message to the old base in order to delete the VCI entry of the call from its call table. The old base acknowledges the message and deletes the entry.

6) The TIU sends a handoff acknowledgment to the mobile through the new base station. This message will include the permanent VCI of the TIU.

7) The conversation proceeds via the new base station keeping the same VCI allocated by the cellular controller at the beginning of the call. This is the key factor in releasing a large amount of the centralized processing load from the network.

VI. PACKET RESERVATION MULTIPLE ACCSESS (PRMA)

The multi-class protocol that the mobile terminal uses to share the short range radio channels that connect them to the base station is a key issue in the design of wireless networks [3]. It is expected that the mobile terminals will be equipped with a speech activity detector. Such a detector will generate packets only if the mobile user speaks. The stream of packets generated then is called a *talk spurt*. The use of such a technique will allow the silence gaps in speech to be used for other talk spurts from other users or to carry data in a mixed media cellular network. Due to the annoying effect of a delayed voice packet, such a packet should be dropped by the protocol if the delay exceeds a certain threshold. Moreover, the protocol should be able to integrate the data without affecting the voice quality.

Before concluding the discussion of the proposed cellular packet switch, a brief description of the associated multiple access technique is due. The PRMA technique proposed for use with the cellular packet switch in [2] can be viewed as a combination of statistical TDMA and slotted ALOHA. The general operation of the PRMA protocol can be summarized as follows [3]:

1) The channel time is divided into slots, each slot is marked as either available or reserved.

2) At the beginning of each frame, those terminals that have packets to transmit and do not own a reservation from a previous frame contend for the 'available' time slots using a random access protocol.

3) If a contending terminal is able to transmit successfully over one of the available time slots, this time slot is marked as reserved. Moreover, the terminal is able to use this time slot for the duration of its talk spurt i.e. until it has no more packets to transmit.

4) At the end of each time slot, the base station transmits a short feedback packet informing all stations whether this slot will be available in the next frame.

5) The base station rejects any packets voice packets that are received after the specified maximum allowable delay.

Figure 4 illustrates this operation. In the figure, terminals 6 & 4 contend for the same available slot in frame k. However, due to collision neither of these two terminal is able to transmit. In frame k+1 a new time slot is available and terminals 6 & 4 contend for two different available time slots in this case (the contention is performed through the random access protocol) they succeed in transmission and obtain reservation. In frame k+2 the only contending terminal is 12 and it obtains reservation. Meanwhile, terminal 8 terminates its talk spurt and its slot becomes available in the subsequent frame.

More details on the performance analysis and voice packet delay calculations of PRMA can be found in [3] while [2] gives a discussion on the combined operation of PRMA and the cellular packet switch.

An important point to be discussed, is the ability of the PRMA to prioritize a certain class of users, e.g. emergency dispatch services or commandants in a mobile tactical network. In a centralized controlled system, multiple access to the network resources is under the controllers authority. Therefor access may be denied or granted upon recognition of the subscriber's identity. Since PRMA is a *random* access discipline, it will be necessary to classify the available time slots into two classes, one which is accessible to all subscribers and the other accessible only to high priority users.

In such a scheme, the cellular controller would mark the time slots as reserved, available or conditionally available. Ordinary users would recognize conditionally available slots as reserved while high priority users recognize it as available. Moreover, they may be encouraged to contend for conditionally available slots instead of available ones.

The classification of available slots will depend on statistics concerning the ratio of ordinary to high priority users currently using the network (obtained possibly from network databases), the number of available time slots in each frame and the specified maximum delays for both types of users. This study is to appear in future work.

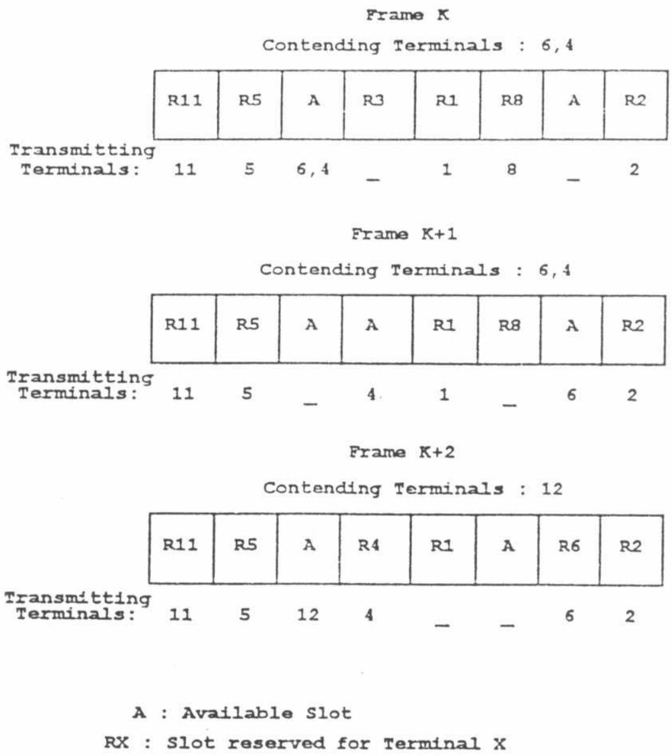

Figure 4. Operation of PRMA.

IV CONCLUSION

It is expected that future cellular systems will be implemented using distributed control. This is predicted from the growing demand on cellular networks leading to tighter cell boundaries which increase the call maintenance processing load. Distributed systems appear to promise greater flexibility, robustness and operating costs. With the current advances in technology, it would be possible to extend the concept of centralized control to the mobile terminals themselves, allowing them to operate as special purpose microcomputers. In this case, many of the decisions which are currently considered *system* decisions will be made in various parts of the network not excluding the mobile terminal itself.

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