DISTRIBUTED MEDIUM ACCESS CONTROL FOR NEXT-GENERATION CDMA WIRELESS NETWORKS

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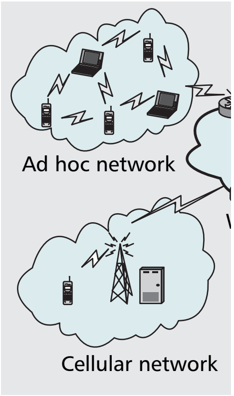

The next generation wireless networks are expected to have a simple infrastructure with distributed control. The authors consider a generic distributed-network model for future wireless multimedia communications with a CDMA air interface.

ABSTRACT

The next-generation wireless networks are expected to have a simple infrastructure with distributed control. In this article, we consider a generic distributed network model for future wireless multimedia communications with a code-division multiple access (CDMA) air interface. For the medium access control (MAC) of the network model, we provide an overview of recent research efforts on distributed code assignment and interference control and identify their limitations when applied in next-generation wireless networks supporting multimedia traffic. We also propose a novel distributed MAC scheme to address these limitations, where active receivers determine whether a candidate transmitter should transmit its traffic or defer its transmission to a later time. Simulation results are given to demonstrate the effectiveness of the proposed distributed MAC scheme.

INTRODUCTION

With the fast-growing Internet technology in an all-IP (Internet Protocol) network architecture, wireless communication systems offer mobile users the convenience of accessing information around the world from anywhere and at anytime. The two most popular and well-deployed wireless networks are cellular networks and wireless local area networks (WLAN). In a cellular network, a mobile user can receive wireless Internet access through its serving base station (BS) and switch to another BS when it moves away from its serving BS, thus achieving global seamless roaming. On the other hand, the WLAN usually is deployed only in local hotspot areas with high-intensity traffic. The major advantages of the WLAN are the high data rate and low deployment cost.

To meet the ever-increasing user demand of multimedia applications in different scenarios, many new wireless networks have emerged, such as ad hoc networks, ultra-wideband (UWB) wireless personal area networks (WPAN), and mesh networks (e.g., as a wireless backbone). A mobile ad hoc network consists of a number of self-organized mobile nodes. An advantage of the ad hoc network is the simplicity of its deployment due to the fact that no pre-existing infrastructure is required, which also makes ad hoc networks suitable to temporary/emergent networks for conference meetings, disaster recovery, and so on. As a special kind of ad hoc network, UWB WPAN can support very high-speed wireless multimedia communications in home and office networking. UWB also has many other benefits such as low power consumption, low interference, and precise positioning capability. In addition to the access networks, wireless technology shows promise in serving as a backbone network in a mesh mode, and thus, is called wireless backbone. A wireless backbone consists of wireless routers at fixed sites [1, 2]. Each wireless router can cover a few access networks such as cellular networks, WLAN, ad hoc networks, and WPAN. The wireless backbone relays traffic among the access networks or between access networks and the Internet backbone (through the gateway). Figure 1 illustrates a network infrastructure for future wireless communications, based on an all-IP architecture. A mobile node with multiple radio interfaces can roam among different wireless networks, to take advantage of the global coverage of cellular networks, the low cost of WLAN, and the high service rate of UWB WPAN.

GENERIC DISTRIBUTED NETWORK MODEL

As illustrated in Fig. 1, many future wireless networks differ from well-deployed cellular networks and WLAN that have central controllers, in that they are expected to operate without central controllers, thus requiring distributed control. Hence, in this article, we focus on a generic network model, where a number of wireless mobile nodes are organized in a flat fashion, communicating with each other via one-hop or multiple-hop connections without any central control. Connections to outside correspondence nodes are supported through a gateway (e.g., in the wireless backbone) or an access point (e.g., in ad hoc networks or WPAN). In the past decade, code-division multiple-access (CDMA) technology was developed

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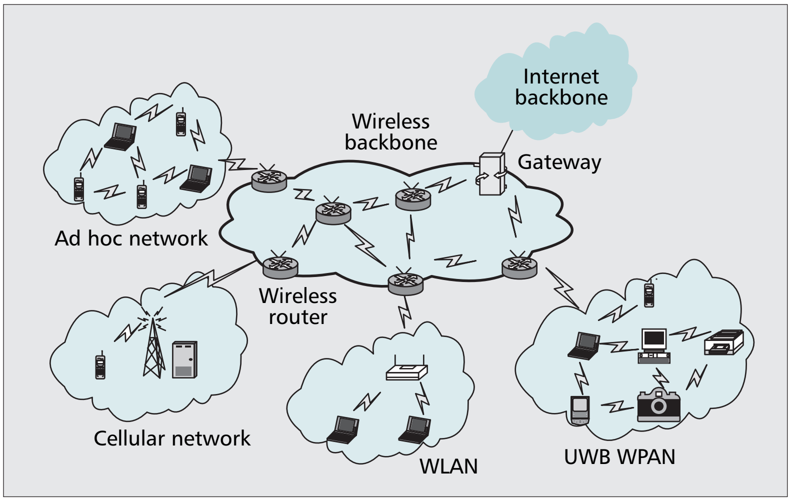

■ **Figure 1.** *An illustration of next-generation wireless networks.*

and deployed with great success in the second-generation (2G) cellular systems (e.g., IS-95). CDMA also was selected as the major multiple-access technology for the third-generation (3G) systems. CDMA has many promising advantages such as universal frequency reuse, soft handoff, and high spectrum efficiency. In addition, the interference-limited capacity of a CDMA system can effectively support multiplexing among multimedia traffic flows. When a previously active source node becomes idle, other nodes will experience less interference. So the "released" capacity (by the idle source node) can be shared by other nodes automatically. This is particularly useful for the IP-based wireless multimedia communications characterized with bursty traffic. Because of these features, we choose CDMA as the air interface for the network model under consideration. The selection of CDMA also is supported by the fact that a spread spectrum technology is being adopted in the current WLAN standards, IEEE 802.11 (although the same spreading code is used by all the nodes), and direct-sequence CDMA was proposed in the literature for the implementation of UWB wireless networks.

Next, we discuss CDMA-based medium access control (MAC) for the generic network model with distributed control.

Desired Features of Distributed MAC

A MAC scheme is used to coordinate the access of mobile nodes to the shared medium such that efficiency can be achieved. Although MAC schemes in traditional cellular networks and WLAN have been extensively studied in the literature, more efforts are needed for distributed MAC supporting multimedia traffic in the network without a central controller.

In a centralized network such as the cellular network, the central controller makes decisions on when and how the mobile nodes should access the medium. However, in a network without a central controller, MAC is carried out in a collectively coordinated manner, where a mobile node determines its access behavior according to its local observation. Desired features of distributed MAC include the following:

Quality of Service (QoS) Support — QoS support is essential for future wireless multimedia communications. The delay-sensitive nature of real-time traffic (e.g., voice or video) determines that its packets should be delivered on a timely basis. On the other hand, non-real-time traffic (e.g., data transfer) usually can tolerate some level of delay but requires a reliable end-to-end transmission, thus transmission accuracy and throughput are desired.

Service Differentiation — In multimedia applications, some traffic flows (e.g., real-time flows) may require timely delivery, and thus, are more urgent than others. Also, some users may be willing to pay more for better service. Thus, service differentiation should be provided among the traffic flows.

Low Overhead — Some local information may be required to be exchanged in the network for distributed MAC. The exchange not only consumes the radio resources (e.g., power, time), but also occupies the system processing time. Therefore, the overhead should be kept at a low level, which also reduces the complexity of the MAC scheme.

Bandwidth Efficiency — The precious radio resources should be utilized efficiently so as to achieve the maximum system capacity (i.e., the maximum number of mobile users that can be supported).

For CDMA-based MAC, two major tasks are code assignment and interference control. In the following, we first summarize recent research efforts on distributed code assignment and interference control, identify their limitations in supporting wireless multimedia applications in our network model, and then present a new MAC scheme to address the limitations.

Distributed Code Assignment

Two popular spread-spectrum technologies are based on direct sequence and time hopping sequence, respectively. Nearby simultaneous transmissions can be supported as long as they use different codes (sequences) with low correlation. Generally, before a transmission, the transmitter and receiver must know the code (sequence) to be used. In cellular networks, the BS collects information from all the nodes and informs them of the codes that will be used in upcoming transmissions. However, as our network model dose not have central authority, distributed code assignment is desired. Three kinds of codes can be used [3]:

- Common code: All the transmissions are based on a common code. This is similar to the case in IEEE 802.11. The drawback is the possibility of collisions among nearby simultaneous transmissions.
- Receiver-based code: Each transmission is based on a unique receiving code of the receiver. The major advantage is that a receiver has the information of the code to be used in any intended traffic. The main concern is the possibility of collisions at a common receiver with multiple intended transmitters.

- Transmitter-based code: Each transmission is based on a unique transmitting code of the transmitter, and therefore the transmissions of two nodes will not collide with each other. However, the intended receiver must know the code in advance.

It is evident that the transmitter-based code is a better choice for data transmission. To inform the intended receiver of the code for data transmission, the request-to-send/clear-to-send (RTS/CTS) dialogue in multiple access with collision avoidance (MACA) can be used [4]. In the MACA common-transmitter-based (MACA/C-T) scheme, an RTS/CTS dialogue spread by a common code occurs prior to the data transmission so that the receiver can identify the intended transmitter and thus recognize the code to be used. The MACA receiver-transmitter-based (MACA/R-T) scheme is different in that RTS and CTS are spread by the intended receiver's receiving code and transmitting code, respectively. As unique codes are used in the RTS/CTS dialogue, the probability of RTS/CTS collisions are reduced. On the other hand, in some scenarios each node may not be able to have unique transmitting and receiving codes in advance. Then a bi-directional multi-channel medium access control (Bi-MCMAC) scheme [5] can be used. Each node collects information of available channels in its own neighborhood (i.e., not being used by others). The RTS contains a list of available channels around the transmitter. Upon reception of the RTS, the receiver selects a channel from the list that also is available in its own neighborhood. The information of the selected channel is included in the CTS and is sent back to the transmitter. The major drawback of the scheme comes from the extra overhead at each node to maintain a record of channels not being used in its neighborhood.

As discussed in the next section, the RTS/CTS dialogue used in the preceding code assignment schemes may become a bottleneck in the network, thus leading to bandwidth inefficiency. New mechanisms are required to avoid the bottleneck effect.

Distributed Interference Control

With proper code assignment to the CDMA transmissions, collisions among them can be avoided. However, the interference among simultaneous transmissions with unique codes also should be managed. Generally, power control can be applied to manage the interference levels in the network, targeting the guaranteed transmission accuracy of each link. Power control can be executed in two manners: global or incremental [6]. A global power control approach reassigns the power levels of all the links in the network at any time when there is a change in link activities, for example, when a new link is admitted or an existing link is completed. This may lead to a very large computation burden and overhead. Therefore, global power control is suitable only for a centralized network with powerful central controllers that have global information of all the links. On the other hand, upon a new link arrival, the incremental power control approach assigns the link a power level and keeps the power levels of all existing active links unchanged. With a much lower control overhead, this power control strategy is more suitable for our network model with distributed control.

In the incremental power control, it is important for a candidate transmitter to know the interference tolerance level of active links. The interference margin or maximum sustainable interference (MSI) [7, 8] of an active link is defined as the additional tolerable interference with the guarantee of required transmission accuracy (e.g., bounded bit error rate). Traditionally the interference margins of active links are advertised within the network. Based on the collected advertisements, a candidate transmitter determines whether it can have a power allocation such that its transmission accuracy requirement is met, and its potential transmission does not generate more interference to any existing active link than the link's interference margin. If such a power allocation is not available, the candidate transmitter defers its transmission. In this procedure, it is essential for an active link to advertise its interference margin. Some interference margin advertisement schemes have appeared in the literature, as discussed in the following.

Aided by RTS/CTS Dialog [8] — Prior to data transmission at a link, there is an RTS/CTS dialog in a separate control channel, and the interference margin of the upcoming data transmission is included in the CTS. Based on the overheard CTS, a nearby candidate transmitter determines whether its interference to the link will exceed the link's interference margin, under the assumption of channel reciprocity. If so, the candidate transmitter defers its transmission. The basic idea behind the interference margin advertisement scheme is to take advantage of the broadcast nature of the CTS transmission. However, as the CTS is not intended for the overhearing candidate transmitter, the CTS may not be received correctly at the candidate transmitter due to the presence of hidden terminals. The RTS/CTS dialogue may also become a bottleneck in the network because of (1) the overhead of the dialogue and (2) the fact that at any time, only one RTS/CTS (thus one data-frame transmission) can be initiated in a neighborhood (otherwise a RTS/CTS collision will happen).

Aided by Busy-Tone Signal from Active Receivers [9] — When a receiver is receiving its data from the sender, it sends a busy-tone signal in a separate busy-tone channel. The power of the busy-tone signal is inversely proportional to the interference margin of the link. A candidate transmitter is required to sense the busy-tone channel prior to its transmission. Based on the detected busy-tone energy, the candidate transmitter estimates the interference margin of the active link and defers its transmission if its interference to that link would exceed the interference margin. The advantage of the scheme is that the bottleneck effect of the RTS/CTS in the previous scheme can be avoided through the use of busy-tone. However, the interference margin estimation is accurate only when there is a single active receiver in the neighborhood of the candidate transmitter. In our network model supporting

With proper code assignment to the CDMA transmissions, collisions among them can be avoided. However, the interference among simultaneous transmissions with unique codes also should be managed.

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multimedia traffic, it is likely that there are two or more active receivers (sending busy tones) near the candidate transmitter and the busy tones may overlap. The candidate transmitter has no information of how many active receivers are nearby and therefore, assumes that the received energy of all the busy tones is from a single active receiver. When the received busy-tone energy is large enough, the candidate transmitter may determine to defer its transmission, although in fact its transmission may co-exist with all the existing active transmissions. Another drawback of the scheme is the assumption that the data and busy-tone channels experience similar propagation attenuation, which may not be true, thus leading to an inaccurate interference estimation.

By Separate Broadcast Channel [7] — A separate broadcast channel is allocated in which the active transmitters can broadcast their interference margins. The major concern in this approach is possible collisions of the broadcast messages. Whenever there is a link activity change in the network, all links should update and broadcast their interference margins. In other words, all the broadcasts occur when the link activity changes, thus resulting in a high probability of collisions. In addition, a candidate transmitter may be required to postpone its transmission until it has collected all the broadcast messages from active links. The access delay can be large.

By a Centralized Leader [10] — Among all the active nodes, one is selected to serve as the leader. The responsibilities of the leader are to collect information about interference margin, transmit power and the location of all active links, and broadcast the information to the whole network. As only one node deals with the interference margin advertisement, the preceding broadcast collision and access delay problems can be avoided. The main drawback is the existence of a leader. Thus the scheme does not scale well to a large network, such as the wireless backbone.

A common feature of the preceding interference margin advertisement schemes is that a candidate transmitter first obtains the interference margin information of all its active neighbors. Based on the estimation of the propagation attenuation from itself to an active receiver, the candidate transmitter estimates its potential interference to the active receiver. The candidate transmitter defers its transmission if it predicts that an existing reception will be corrupted by its potential transmission. Such a procedure has several drawbacks. The candidate transmitter must know which nodes are receiving packets in its neighborhood. The accuracy level of the prediction is impaired by incomplete or out-of-date information of the interference margins of active links. Also, the propagation attenuation estimation from the candidate transmitter to an active receiver may not be accurate, as the estimation is done at the candidate transmitter, not at the active receiver.

These drawbacks result mainly from the fact that the candidate transmitter performs (on behalf of an active receiver) the channel estimation (from the candidate transmitter to the active receiver) and interference estimation seen at the active receiver. One way to avoid the drawbacks is to allow the active receiver to perform the estimation. Thus, for our network model, we propose that the active receivers, rather than the candidate transmitter, determine whether the candidate transmitter can transmit its traffic or should defer its transmission to a later time. This is because a possible corruption happens at an active receiver rather than at the candidate transmitter. In this way, no interference margin advertisement is required. The code assignment also should be different from the previous RTS/CTS-based code assignment, as the RTS/CTS dialogue is no longer required (for interference margin advertisement). We will elaborate on this in the following section.

The Proposed Distributed MAC

In our network model, the MAC is to coordinate the one-hop transmission from a transmitter to one of its neighbors. Each node has its own transmitting code and receiving code, the information of which is available to its neighbors through some information exchanges in the routing protocol. The basic QoS requirements for the traffic transmission are a bit-error rate (BER) upper bound and a minimum transmission rate. The BER upper bound can be mapped to a signal-bit energy-to-interference-plus-noise density ratio (SINR) threshold. The transmission rate requirement can be determined to guarantee the packet-level QoS of the traffic (e.g., delay for voice and video and throughput for data). For instance, the *effective bandwidth* of a traffic flow can be used as the transmission rate requirement.

To avoid the interference margin advertisement to the whole network, the active receivers can be designed to determine whether a candidate transmitter should transmit. A candidate transmitter is required not to corrupt the transmission accuracy of ongoing active links; otherwise, the candidate transmitter should defer its transmission. In this context, it is essential to

- Make each active receiver aware of a possible increase in its experienced interference due to the potential new transmission
- Make the candidate transmitter aware of the decisions made by the active receivers

In our network, a probe is used by the candidate transmitter to implicitly inform an active receiver of the potential increase in interference level, and a busy-tone channel is used by the active receivers to feed back their decisions. Thus, the network uses a CDMA-based data channel on a large frequency band and a single-frequency busy-tone channel on a separate small frequency band.

The network uses a synchronous time-frame structure. For large networks such as a wireless backbone, the synchronization can be achieved with the aid of the global positioning system (GPS). For small networks, such as ad hoc networks or WPAN, the synchronization can be achieved by allowing a selected node to send an out-of-band beacon signal. Each frame has a constant duration and consists of M slots, and each slot is further divided into N mini-slots, as shown in Fig. 2. Data frames are sent in the slots, and the probes and busy tones are sent in the mini-slots.

To illustrate the MAC procedure, consider a scenario in Fig. 3 where there are a number of active links and a potential new link from node j to k with a burst of traffic arrival at time frame $l-1$ ($l \geq 1$). Each of the active receivers estimates its interference increase due to the potential new transmission from node j to k, that is, in a distributed way. Among all the active receivers, node i is selected as an example. All other receivers carry out a similar procedure as that of node i. The detailed operations of the candidate transmitter (node j), the candidate receiver (node k), and the example active receiver (node i) are described as follows.

Step 1 (at Frame l) — At mini-slot 1 of each slot, node j measures its experienced interference in the data channel. It also monitors the node k's transmission activity by scanning the transmitting code of node k. Among the slots without transmission activity of node k (note that node k cannot transmit and receive at the same slot in the data channel), node j selects a slot with the minimal detected interference level as its transmission slot, denoted by m.

Step 2 (at Frame l + 1, Transmission Slot m) — Among mini-slots 2 to N, node j randomly selects one (denoted by ID n) to transmit a probe via a common probe code. The transmit power is ξ_p ($\ll 1$) times P_{jk} (the transmit power level for data transmission from node j to node k).[1] The reason to use a small power level is to not corrupt the transmission of any active link. A large spreading gain is used by the probe to facilitate the reception of the probe at the active receivers. No bit information is carried in the probe. Upon reception of the probe, node i estimates its increased interference due to the potential data transmission from the probe transmitter (i.e., node j) as $1/\xi_p$ times the measured probe power. Then, based on its own interference estimation at mini-slot 1, node i determines whether it can tolerate the extra interference by node j. If not, it sends a busy tone in the busy-tone channel at mini-slot $n + 1$ (if $n = N$, the busy tone is sent at mini-slot 1 of the next slot). If node j detects a busy tone at mini-slot $n + 1$, it selects another transmission slot and repeats the procedure from step 2; otherwise, the node proceeds to step 3.

Step 3 (at Frame l + 2, Transmission Slot m) — Node j sends a request message to its receiver, that is, node k, via node k's receiving code, using power level P_{jk}. A processing gain larger than that of data transmission (through a more powerful channel coding) is used so that the message can be received correctly. The measured (by node j) interference level at each slot is also included in the message. Upon reception of the message, node k determines whether a target SINR can be guaranteed for the potential data transmission with a normal processing gain. If yes, node k selects an ACK slot over which node j experiences the minimal interference under the constraint that neither node j's transmission nor node k's reception already occurs at the slot. Then at the ACK slot node k transmits a confirmation to node j via node k's transmitting code, with power $\xi_a P_{kj}$ ($\xi_a \ll 1$). As the number of information bits in the confirmation is much less

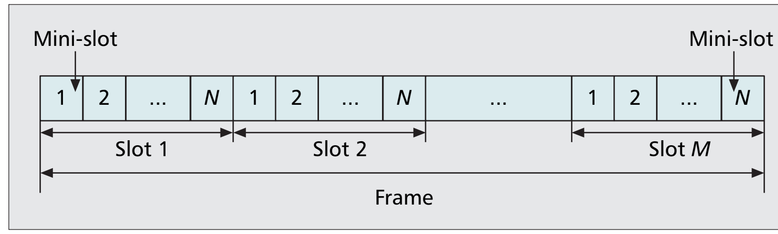

Figure 2. *The time frame structure.*

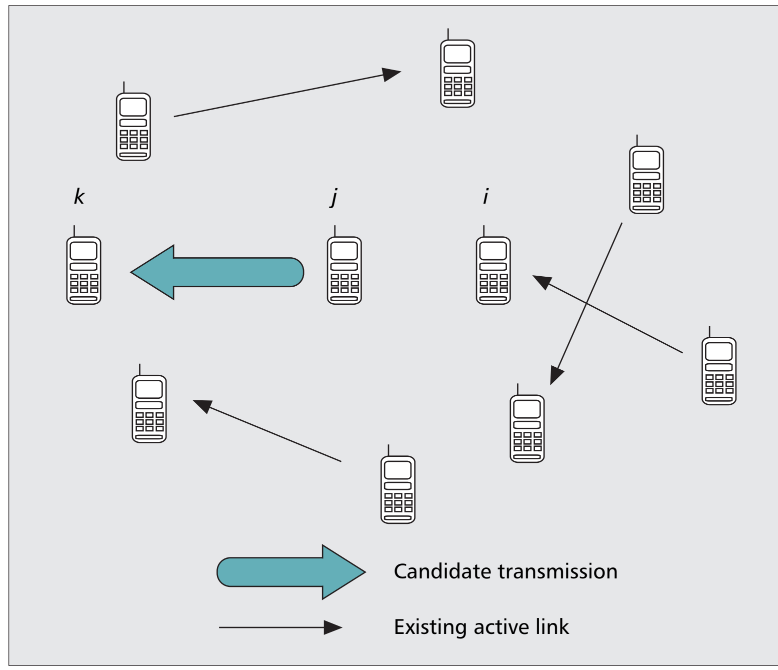

Figure 3. *A network scenario for illustrating the MAC procedure.*

than that in a data frame, a large processing gain can be used to guarantee correct reception of the confirmation.

Step 4 (at Subsequent Frames) — At transmission slot m, node j transmits data frames with power P_{jk} via its transmitting code. At the ACK slot, node k sends an acknowledgment (ACK) for the correctly received traffic via its transmitting code, with power $\xi_a P_{kj}$ and the large processing gain. This continues until the completion of the transmission of all data frames in the burst (from node j to node k), that is, a burst-level resource reservation is used. After the completion of the burst transmission, no associated operation is required. Each remaining active receiver will experience less interference, thus increasing its tolerance level to extra interference accordingly. As a comparison, in the aforementioned interference margin advertisement schemes, other remaining links or the centralized leader should be notified of the link departure and should update and broadcast their new interference margins.

The medium access procedure is illustrated in Fig. 4. In the annotation for each transmission, the first and second terms denote the code and transmit power level used, respectively.

If the transmission rate request of node j cannot be accommodated by only one transmission

[1] The transmit power level in the data channel may be a constant or dependent on the location of the transmitter and the receiver, if the location information is available (e.g., in a wireless backbone).

slot, node j may seek transmissions at more slots until the rate requirement is satisfied. In addition, when the traffic load in the network is light, adaptive resource allocation should be exploited for better bandwidth utilization. This can be done in two ways: multi-code transmission — when a receiver measures a higher SINR than the required value, it informs the transmitter to increase the transmission rate by parallel transmissions spread by mutually orthogonal subcodes; multi-slot transmission — when, in addition to the slots being used, a transmitter seeks transmissions at other slots over which both the transmitter and receiver experience low interference. When an active receiver senses a probe from a candidate transmitter, the receiver may inform its transmitter to decrease the data rate (i.e., to reduce the number of parallel transmissions, or the number of transmission slots) so that the candidate transmitter can join the network.

From the preceding discussion, the proposed MAC scheme can (or has the potential to) fulfill the aforementioned desired features:

- QoS support: The bit-level QoS (i.e., BER) is met by the interference control. The packet-level QoS can be satisfied by the burst-level resource reservation mechanism, as long as the reserved resources can meet the transmission rate requirement.
- Service differentiation: Service differentiation can be incorporated into our scheme. If a candidate transmitter selects a mini-slot with a larger ID for its probe, it is less likely to join the selected slot because the available resources at the slot may be reserved by other new links at earlier mini-slots (with smaller IDs). Thus, for high priority traffic, the candidate transmitter can select to send its probe at a mini-slot with a small ID, thus gaining a relatively advantageous position in the medium access.
- Low overhead: Because of no requirement for interference margin advertisement, a low overhead can be achieved in our scheme.
- Bandwidth efficiency: Although based on the same interference margin concept as those previously proposed in the literature, our distributed MAC scheme can eliminate the high overhead due to interference margin advertisement. Also, as the channel and interference estimation are done at the active receivers rather than at the candidate transmitter, accurate estimation can be achieved, thus avoiding potential bandwidth waste due to channel and interference estimation errors.

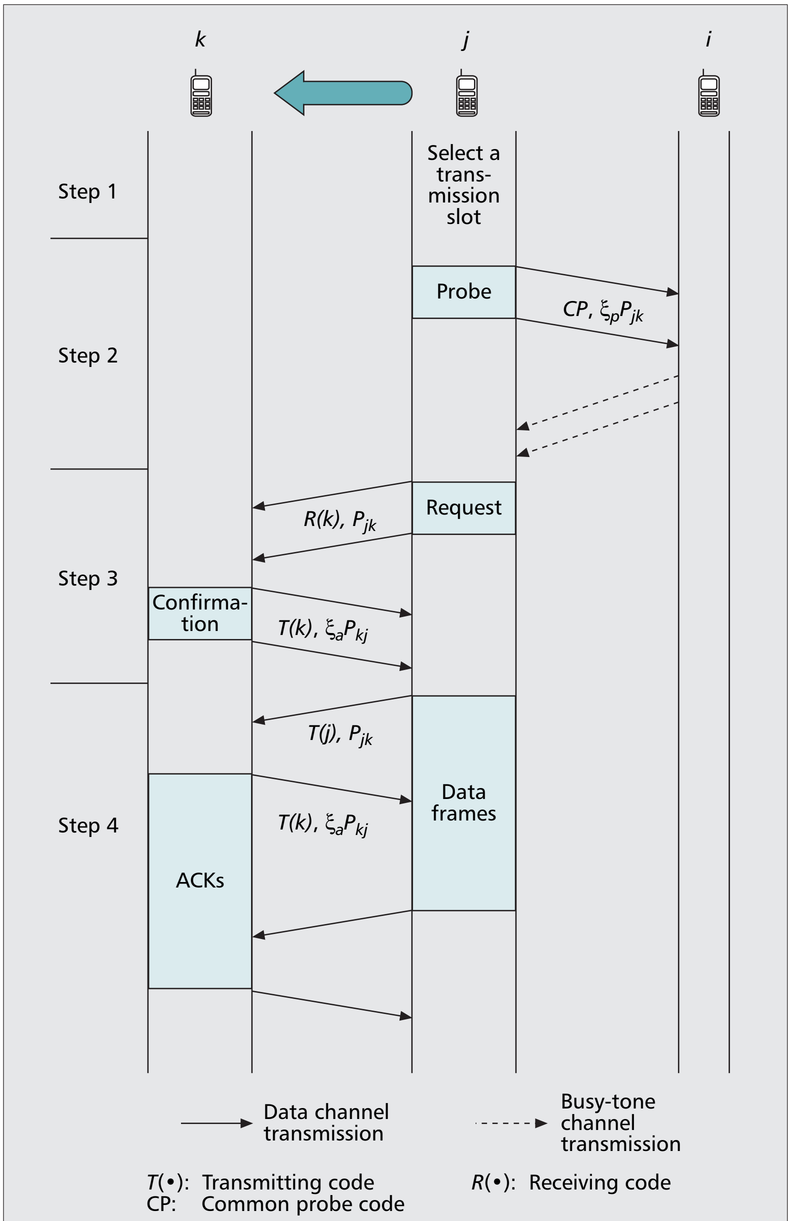

Figure 4. *The procedure of the proposed distributed MAC.*

Bandwidth Efficiency Evaluation

We ran computer simulations to evaluate the bandwidth efficiency of our proposed MAC scheme. A CDMA-based data channel was used with a chip rate equal to 50 Mchip/s and with a spreading gain equal to 64. Consider a network with four data source nodes and four corresponding destination nodes randomly distributed in a 100 m × 100 m square. Traffic burst arrivals at each source node follow a Poisson process. Background noise is neglected in the simulation. When active, each source node transmits with a constant power level. The transmit power is attenuated with a propagation path loss exponent 2.4, while the fast fading is assumed to be addressed by the RAKE receiver. The SINR threshold is 5 dB. The frame duration is 20 ms. Other simulation parameter values are: $M = 4$, $N = 10$, and $\xi_p = \xi_a = 0.01$. As a comparison, we also simulate the RTS/CTS-based interference margin advertisement scheme in [8]. We gradually increase the traffic load in the network and obtain the aggregate throughput performance of the two schemes as shown in Fig. 5. It is observed that the RTS/CTS-based scheme becomes saturated when the traffic load increases to 8 Mb/s, while our scheme does not reach the saturation until the traffic load is above 30 Mb/s. The gain is due to the removal of the RTS/CTS information exchange from the access procedure, thus avoiding the bottleneck effect.

Conclusions

We have discussed the limitations of existing distributed CDMA-based MAC schemes when applied to our generic network model with distributed control. By allowing active receivers to estimate the potential increase in the interference level, our proposed MAC scheme can achieve bit-level QoS, low overhead, accurate channel and interference estimation, and high bandwidth efficiency. Our scheme also has the potential to support packet-level QoS and service differentiation.

The MAC scheme only deals with the transmission from a source node to one of its neighboring nodes. For a future distributed network supporting multi-hop transmissions, MAC should be jointly designed with call admission control and routing so as to achieve (call-level) end-to-end QoS support and overall bandwidth efficiency. Many open issues (such as interference/ congestion-aware routing and distributed call admission control) in the area require further research.

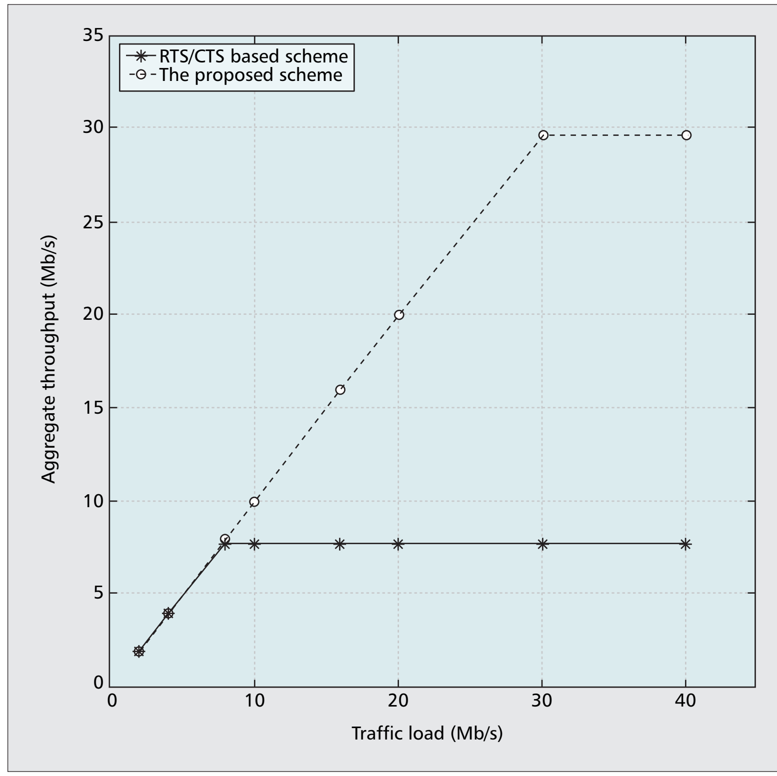

Figure 5. *Throughput comparison between the proposed scheme and the RTS/CTS-based interference margin advertisement scheme.*

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